Université Sorbonne Paris Nord

École doctorale Galilée
Sciences, Technologies, Santé

Habilitation à Diriger des Recherches (HDR)
Discipline : Informatique

Saadi BOUDJIT

Wireless multi-hop ad hoc networks: From WBANs to Large Scale Topologies

Submitted in total fulfillment of the requirements of the degree of Habilitation à Diriger des Recherches

Committee:

Reviewers:	Juan Carlos Cano	Pr. Polytechnic University of Valencia
	Bernard Cousin	Pr. Université Rennes 1
	M. Dias de Amorim	Directeur de recherche CNRS
Examiners:	Paul Mühlethaler	Directeur de recherche INRIA Paris
	Sherali Zeadally	Pr. University of Kentucky
	Laure Petrucci	Pr. Université Sorbonne Paris Nord
	Ken Chen	Pr. Université Sorbonne Paris Nord

Contents

Chapter 1

Introduction

1.1 Foreword

This manuscript summarizes the main research activities I carried out during the last ten years. My research interests focused on some issues related to two main architrectures of wireless ad hoc networks, namely Wireless Sensor Networks (WSNs) and Vehicular Ad hoc Networks (VANETs). We were working on routing and Quality of Service (QoS) in Wireless Body Sensors (WBANs), and on the design and evaluation of routing protocols for Large Scale WSNs (LSWSNs) and Vehicular Ad hoc Networks (VANETs/Drones). This document is the result of a number of collaborations worldwide but mainly the result of my research conducted with my PhD students. I express my sincere appreciation to all of them without whom these results would not have been achieved.

1.2 Context: wireless multi-hop ad hoc networks

A Mobile Ad hoc Network (MANET) is a collection of devices/nodes or terminals with wireless communications and networking capabilities that communicate with each other over wireless links and without the aid of any centralized administrator. It is an independent system of mobile nodes that may operate in isolation, or may have gateways to interfere with a fixed network. In an ad hoc network each node functions as both a host and a router. Hence, packets to be exchanged between two nodes that are not in direct range with each other are relayed by intermediate nodes. These messages are exchanged and relayed between nodes using a routing protocol. However, due to the mobility of the nodes, the topology of the network may rapidly be changing, making it impossible to use conventional routing tables maintained at fixed points (routers). Instead, each node is required to determine the best route to a given destination node by itself. In this context, several years have been spent by research community in designing routing protocols for ad hoc networks and numerous ad hoc routing solutions have been proposed within the MANET working group in the IETF (Internet Engineering Task Force). Some of these proposals have been promoted to experimental RFCs (Request For Comments) like OLSR [19] and AODV [69]. None of these protocols, however, is applicable in state when considering a real application of ad hoc networks. If we consider vehicular networks, these routing protocols should be adapted to the context of high mobility of the nodes and frequent topology changes. In this case, the main point that can be identified is the optimized management and control of the information broadcast.

During the last ten years, we were interested in designing efficient data dissemination techniques and quality of service schemes while targeting some major applications of wireless ad hoc networks. We focused our works on three important applications of wireless ad hoc networks, the wireless body sensor networks WBANs, the large-scale wireless sensor networks LSWSNs, and the vehicular networks (classical Vehicular Ad hoc Networks VANETs and Unmanned Aerial Vehicles UAVs or Drones). In these networks we were particularly interested in the following aspects:

- Routing, QoS at MAC level, Cross Layer Architectures and Interference in WBANs.
- Routing, Duty Cycling, QoS, Deployment and energy management in LSWSNs.
- Geo-localized routing in VANETs and bio-inspired routing in UAV networks.

In the following three sections, I will give an overview on the previously mentioned applications of wireless ad hoc networks and highlight our main contributions in each of them within supervised and finished PhD thesis. Some other works within other ongoing PhD thesis are not part of this manuscript. Finally, a summary of some other contributions mainly done within Co-supervised PhD thesis will be given in Annex B.

1.3 Wireless Body Area Networks

Recent advances in wireless networked systems, intelligent low-power sensors and medical sensors, have led to the development and emergence of new embedded networks in the last years known as Wireless Body Area Networks (WBANs). The WBANs carry the promise of expanding the quality of life and care across a large variety of healthcare applications. These wearable health monitoring systems aim to support early detection of abnormal conditions and prevention of their serious consequences. In addition to the embedded medical sensors and a coordinator acting as a gateway for the WBAN, these systems are based on information technologies and wireless communication as depicted in Figure 1.1. Patients benefit from continuous ambulatory monitoring as a part of a diagnostic procedure, optimal maintenance of a chronic condition or during supervised recovery from an acute event or surgical procedure.

However, to set up such systems several issues along the communication chain should be resolved. The acquisition and dissemination of medical data, the treatment and use

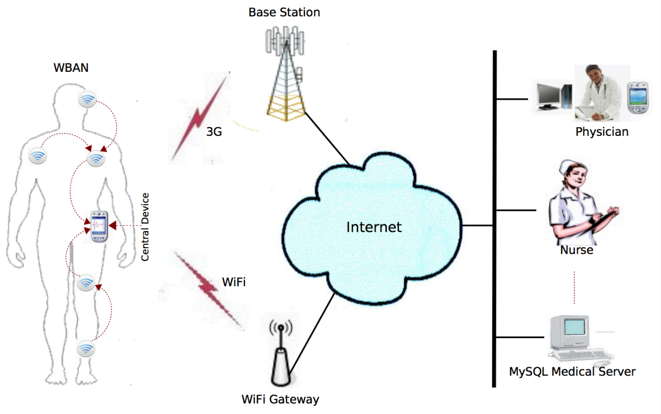


Figure 1.1 – Wireless health monitoring system

of this data either by a local contractor equipment (coordinator of the WBAN) or offset after transfer in 4G/5G and/or WiFi connection to a data server, confidentiality and data security, QoS over a WBAN, end-to-end QoS over WBAN's heterogeneous peer-networks, ...etc. are some of the important challenges that should be considered. Moreover, embedded sensors in a WBAN have limited energy resources available and consequently the computational power and available memory of such devices are limited. This poses a number of challenges on the design of communication protocols for WBANs.

Contributions

In this context, we first proceeded with a deep analysis of the energy consumption of one-hop vs multi-hop communications in WBANs. We have analyzed the single vs multi-hop energy consumption effect for real very short range sensor devices.
Based on the obtained feedback, we then designed energy efficient routing protocols for intra-WBAN and inter-WBANs data dissemination; these protocols aim to reduce the energy consumption of the nodes and therefore increase the network lifetime.

We next tackled the problem of data aggregation at the Medium Access Control (MAC) layer of a WBAN. We designed a cooperative MAC protocol for intra-WBAN communication; this protocol merges frames at the relaying nodes to increase data exchange without overloading the whole network flow with control data.

We further addressed the Quality of Service (QoS) for WBAN to peer-networks communication. We developped a scheduling technique at the coordinator of a WBAN to mitigate the waiting time of some traffic classes such as emergency, high-priority and medical data over other classes.

1.4 Large Scale Wireless Sensor Networks

A Sensor Network consists of a number of sensors spread across a geographical area. Each sensor has a wireless communication capability and sufficient intelligence for signal processing and networking of the data. However, it has limited resources in terms of battery energy, bandwidth, memory, and computational power. Collaboratively, these devices establish a network to monitor activities in their sensing range and then the captured information is transmitted via wireless communication to a data collection center called Sink. Limited energy resource limits communication range and Sensors-Sink communication could be over multi-hops. Therefore, a multi-hop routing protocol to compute the paths between the sink and all the sensors is needed. The scale of such networks ranges from few medical sensors attached to the human body to hundreds and thousands deployed in large harsh terrains for habitat monitoring, battle fields, and intrusion detection applications. Since communication is the most power consuming task in WSNs and battery replacement is not possible in many of these applications, any proposed protocol for WSNs should consider the energy consumption constraint. Indeed, sensors may be randomly spread by an airplane, for example, over a large harsh terrains or an enemy area, and are not human accessible once deployed. Self-organization and data dissemination techniques that ensure longer network lifetimes while respecting application requirements and minimum control overhead are an utmost necessity.
Majority of the routing algorithms found in the literature propose static sink-based data dissemination. However, the static sink can be seen as a bottleneck in enhancing network's lifetime, since nodes close to sink die quickly due to excessive relaying.

Contributions

We focused our work on energy efficient routing in large scale wireless sensor networks with the aim of improving network lifetime by distributing relay nodes' energy consumption. We have adopted a WSN with a mobile sink and two distributed energy-efficient sink location update algorithms were proposed for large scale mobile sink WSNs. First algorithm, named SN-MPR and suitable for delay sensitive applications, uses a combination of multi-point relay broadcast and local path repair mechanism by means of which sink's location update packets are forwarded only to nodes which are affected by sink mobility; the rest of the network does not receive these update messages.

We then proposed a Duty-Cycle aware multi-point relay based routing algorithm. It is a modified version of SN-MPR, suitable for delay tolerant applications, which allows non-relay nodes to switch-off their radios when communication is not desired and hence, save their batteries' energy and improve global network lifetime.

1.5 Vehicular Networks

Smart vehicular networks provide one of the most important research field over the past ten years. They are considered as an application of Mobile Ad Hoc Networks (MANETs) and are widely based on MANET fundamentals. They are characterized by a high mobility of the nodes, frequent changes in topology, high and frequently variable density, and regular moving patterns. Among the existing applications of vehicular networks, VANETs and UAVs are the ones having the most increasing interest for the valuable assistance they can bring to different sectors.

Vehicular Ad Hoc Network (VANET) is a network of cars established for a specific need or situation. Vehicles in a VANET are equipped with embedded smart communication boxes called On-Board Units (OBUs) that communicate with each other via vehicle-to-vehicle communication (V2V) and with deployed ground base stations called Roadside Units (RSUs) via vehicle-to-infrastructure communications (V2I). Vehicular ad hoc networks (VANETs) are becoming an ubiquituous technology for the high interest that Intelligent Transportation Systems, ITS, can offer through them in both saving lives, time, energy and the planet. They have now been established as reliable networks that vehicles use for communication purpose on highways or urban environments.
To ensure autonomous multi-hop communication between vehicles on the road for the purpose of traffic management, safety alerting or infotainment, VANETs provide a large range of routing protocols in the literature. However, most of them result from the long theoretical work done in the framework of MANETs and not well adapted to realistic situations. In our study, we considered the Geocast routing technique which better meets the different needs of ITS in terms of dissemination of safety information as well as traffic management, and tried to propose efficient multi-hop routing schemes to cope with QoS requirements and specifically to save bandwidth.

Unmanned Aerial Vehicles (UAVs) is another application of vehicular networks we targeted in our study. Drones or UAVs have long been a military tool, however, in recent years, they are of increasing interest and their use has been extended to the civilian sector and being used in different fields ranging from real-time applications such as forest fire surveillance and highways traffic monitoring, to delay-tolerant applications such as parcel delivery. The use of UAVs in such applications allows to save money since they can replace manned planes and helicopters. Indeed, there are small, lightweight, and cheap UAVs capable of replacing humans in civilian missions such as surveillance of environment, monitoring, search and rescue of survivors after disasters [62], and borders control [78]. Some of these applications could be carried out more efficiently with a fleet of drones deployed in an ad hoc manner and operating collaboratively. However, these UAV networks could be faced to several issues that can lead to a degradation of their performance. The main issues are the high mobility of UAVs and the rapid changes of the network topology. This can lead to frequent disconnection of radio links, large queues, and loss of transmitted packets. These issues are even more problematic for real-time applications where ensuring a good connection between UAVs in order to avoid frequent disconnections of radio links is a primary objective. Several works in the literature have tried to solve these problems, but in most of them UAVs act as relays for data exchange between two or more distant ground groups or users [32][45]. In this context, we tried to propose efficient routing schemes to cope with frequent link failures specifically for time-sensitive applications.

Contributions

In the context of VANET networks, we proposed a Geocast routing protocol named GeoSUZ where a message is routed from a source vehicle to all vehicles located in a well geographically defined destination area called ZOR (Zone Of Relevance). We considered a ZOR as a set of sub-ZOR and provided a geometrical vision angle based technique to define if two sub-ZORs are in the same direction in order to send them a single message, and hence, reduce messages overhead and save bandwidth.

We then proposed a bio-inspired routing protocol for collaborative Unmanned Aerial Vehicles (UAVs) called BR-AODV. The protocol takes advantage of a well known ad hoc routing protocol for on-demand route computation, and a swarm intelligence technique for connectivity and route maintaining while data is being transmitted.

1.6 Outline of the manuscript

The core of this manuscript is composed of three chapters, Chapters 2, 3 and 4. They present our main contributions in the three groups of networks described in the previous section. In these chapters, I get into the details of the proposed solutions and try to give a complete view of the problem. However, I do not present the results of the performance evaluation of the proposals. For more details on each proposal, the reader is invited to refer to the corresponding publications. In Chapter 5, I present a summary of the manuscript and raise a number of issues as a plan for future research directions.

This manuscript also includes two annexes, A and B. In Annex A, I briefly highlight a number of other contributions that are not presented in the core of this manuscript. The Annex B summarizes my main publications. For a complete view of my research activities, the reader can refer to my webpage at https://www-l2ti.univ-paris13.fr/∼boudjit/.

Chapter 2

Wireless Body Area Networks

This chapter summarizes our contributions at Network and MAC layers in wireless body area networks. I will first present a comparative study of intra-WBAN routing schemes and a NetBAN, a concept of network of BANs, designed for inter-WBANs cooperation with a routing protocol to optimize energy consumption. Then I will present a decode and merge cooperative mechanism defined at the MAC level for intra-WBAN communication. The last contribution deals with the QoS in WBANs. For this end, a Priority Weighted Round Robin (PWRR) scheduling technique at the coordinator to bridge sensitive data from WBAN to peer-networks will be presented. These contributions are mainly done within the PhD thesis of *Audace Manirabona* and *Hadda Ibn Elhadj*.

2.1 Intra-WBAN Data Dissemination

Publications : [1][11][16][34][35][39][43][48]

Several studies have shown that multi-hop routing in WBANs result in non-negligible lifetime increase of sensors as compared to direct communication between sensors and the central device. Some other studies, however, argue contrarily. They show that direct communication between sensors and the central device considerably increase the lifetime of the wireless body area network. In this section we are exploring both information dissemination techniques in a WBAN. The objective is to find a trade-off between the number of hops in the network and the optimum overall energy consumption.

2.1.1 Problem Analysis

Power consumption for transceivers is different in different communication states i.e. transmission/reception/idle/sleep. Unlike other technologies, reception/idle state consumption for low power, limited range WSNs is not negligible as compared to trans-

mission state power consumption. Thus global energy minimization requires optimum selection of transmission range. Latré et. al. in [56] showed that utilizing multi-hop communication by reducing transmission power in WBANs reduces overall energy consumption. This is true but authors in [56] ignore increased energy consumption due to multiple receptions. Indeed, real experiments conducted in [5] show that reception and idle listening consume a considerable amount of energy. They show that for sensors with very low transmission ranges as in WBANs, transmission consumes lesser power than reception. This is true for Crossbow' micaZ motes [1] where reception energy is higher than transmission energy even with maximum power transmission. Wang et. al. in [71] propose a power consumption model for WSN where they show that power controlled multi-hop communication does not neccessarily result in energy gain.
Above stated variations in literature, motivated us to better understand this energy consumption scenario and choose a better routing strategy in a WBAN.

Channel model and Energy Consumption

Let P_t and P_r be the transmission and reception signal power respectively, where P_r is equal to receive sensitivity of mica2 node (-98 dBm). Let d be the communicating nodes' inter-node distance and, L the system loss, then our WSN model can be represented by the well known *TwoRayGround* radio model:

$$P_r = ReceiveSensitivity = \frac{P_t G_t G_r h_t h_r}{d^4 L} \tag{2.1}$$

Where G_t=G_r=1.2 are antenna transmission and reception gains respectively. h_t=h_r=16cm are transmission and receptor's antenna heights. Transmission power P_t is varied according to desired range. Equation (2.1) can be rearranged to determine d for given values of P_t as follows:

$$d = [\frac{P_t G_t G_r h_t h_r}{P_r L}]^{\frac{1}{4}} \tag{2.2}$$

We need minimum P_t that ensures successful reception of packet at destination with P_r>*ReceiveSensitivity*. For given values of P_t, approximate range values are obtained from radio model given in (2.2). The actual power consumed by a Crossbow mica2 mote while transmitting with permissible power P_t is obtained from its corresponding CC1000 data sheet [2]. The range results for given P_t (Table 2.1) conform to the MICA2 data sheet and experimentally obtained range values.

Energy consumption of sensor nodes in various states can be obtained by the following equations:

[1] http://www.ti.com/product/cc2420
[2] http://www.ti.com/lit/ds/symlink/cc1000.pdf

Tx power (dBm)	Power consumed (mW)	Rx power/Idle power (mW)	Tx range (meter)
05	76.2	30	60
-07	32.4	30	30
-14	27.9	30	20
-20	25.8	30	10

Table 2.1 – Mica2 Mote Power Consumption and Range Values

$$E_{tx} = P_{tr} \times T_{tx}$$

$$E_{rx} = P_{rec} \times T_{rx}$$

$$E_{idle} = P_{idle} \times T_{idle}$$

where P_{tr}, P_{rec}, P_{idle} are the powers consumed by the Mica2 mote's CC1000 transceiver in transmission, reception and idle mode respectively, and T_{tx}, T_{rx}, T_{idle} are times spent in each mode. Time for transmitting a packet of size b bits is equal to $[\frac{b}{R}]$ where R is the data rate. Total energy consumed by the network is given by;

$$E_{total} = E_{tr} + E_{Rec} + E_{idle}$$

2.1.2 Simulation and discussion

We performed simulations utilizing the actual power consumption values of sensor motes in various states. In order to have an insight view of the energy consumption in various working modes, the power consumption values of Crossbow Mica2 sensor motes have been used. Crossbow Mica2 motes have a Texas Instruments on-board chipcon's CC1000 transceiver for communication. Thus power consumption values for communication have been taken from the previously referenced CC1000 data sheet.

Deployed topology consists of a set of seven equidistant nodes $\{n_s, n_2, n_3, n_4, n_5, n_6, n_d\}$ deployed linearly with adjacent inter-node distance of 10 meters. This accounts to maximal source-destination ($n_s \rightarrow n_d$) distance of 60 meters. Source n_s generates packets at regular intervals and transmits them towards sink n_d. Simulations are performed

Scenario	Hops	Distance	Nodes
1	1	60	$n_s \rightarrow n_d$
2	2	30	$n_s \rightarrow n_4 \rightarrow n_d$
3	3	20	$n_s \rightarrow n_3 \rightarrow n_5 \rightarrow n_d$
4	6	10	$n_s \rightarrow n_2 \rightarrow n_3 \rightarrow n_4 \rightarrow n_5 \rightarrow n_6 \rightarrow n_d$

Table 2.2 – Considered scenarios

with four different relaying scenarios. Details are given in Figure 2.1 and in Table 2.2. Transmission $n_s \rightarrow n_d$ is varied from single hop to a maximum of six hops.

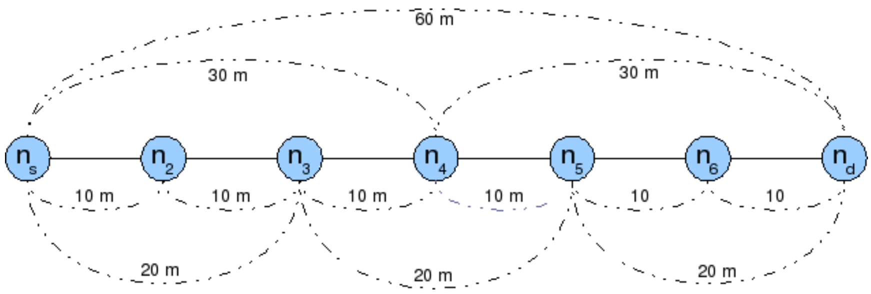


Figure 2.1 – Considered scenarios

We simulated the total network energy consumption when radio is always active i.e. either in Tx/Rx state or in idle state. We also simulated the total network energy consumption when nodes switch on their radio only when they need to transmit their information. The obtained results show that at very low ranges, transceivers consume almost equal or more power on reception than transmission.

Discussion

An energy consumption comparison for various communication scenarios has been made. It has been shown that at very low ranges, transceivers consume almost equal or more power on reception than transmission. Though this is device dependent, general characteristics of very low power transceivers seem to show the same results. Thus deliberate reduction of transmission range to induce multi-hop scenario is not efficient.
However, in some cases in WBANs, sensors will not be able to communicate directly with the coordinator. In fact, according to [73] and [27], around the human body a path loss exponent α of about 3 to 4 is reached in Line Of Sight (LOS) communication and a path loss exponent of 7 is found when the communication is Non-line Of Sight (NLOS) (e.g., when the sender is placed on the back and the receiver on the chest).

In this case, the central device may not be able to receive a packet transmitted by the sensor as the signal gets absorbed by the human body. If such a condition arrives, the data dissemination mechanism in use should be able to transmit data to the personal coordinator on multi-hop via another health sensor installed on the body.

From the aforementioned discussion, it is concluded that unless really required, unnecessary multi-hop relaying in case of WBANs should be avoided. However, to cope with the attenuation factor mentioned above, we proposed number of scenario driven and energy efficient cross-layer 2-hop data dissemination algorithms that would allow nodes to communicate with the central device over two hops, when required. The assumption of using maximum two hops seems logically correct as this option will be used in only special scenarios described above. In addition, our assumption of considering two hops has also been enforced by the IEEE 802.15.6 WPAN Task Group 6 [2] which recently recommended to consider 2-hops topologies for routing in WBANs.

2.2 Inter-WBANs Data Dissemination

Publications : [7][36]

The main key applications of WBANs include first the healthcare by supplying assistance to elderly population or patients at hospital or at home [44][47]. They include secondly the entertainment where people, for instance, can play game in group or exchange some data such as visit cards though handshake, but also the sport where athletes or other sportsmen in workout can be monitored to increase their performance [18]. Finally, there is military area, where, like sport area, soldiers can be assisted and share data [47]. For many of these application, the WBANs can cooperate in exchanging or relaying data to achieve many goals: optimize energy consumption, prolong network lifetime, allow group navigation, improve data delivery, etc. Indeed, considering the case of a group of WBANs such as elders in retirement home or athletes on work out, it is important to ensure data transmission even in the critical situation: connection lost, energy lack or poor network coverage. Taking advantages of the group interactions, relaying and cooperation would solve those issues and increase packet delivery ratio while optimizing energy consumption. This concept of cooperation is what we call "NetBAN". The NetBAN is a special ad-hoc network given the different communication paths expected to occur. Unlike the simple ad-hoc network where communication links are homogeneous, a NetBAN has heterogeneous communication links: coordinator to coordinator, node to coordinator or node to node (Figure 2.2).

Taking the aformentioned applications, the cooperation need can occur in two main situations: whether the residual energy is not enough (under a given threshold) or connection is lost (the link quality is under a certain threshold). The cooperation may thus be carried out at three different communication levels; coordinator-coordinator cooper-

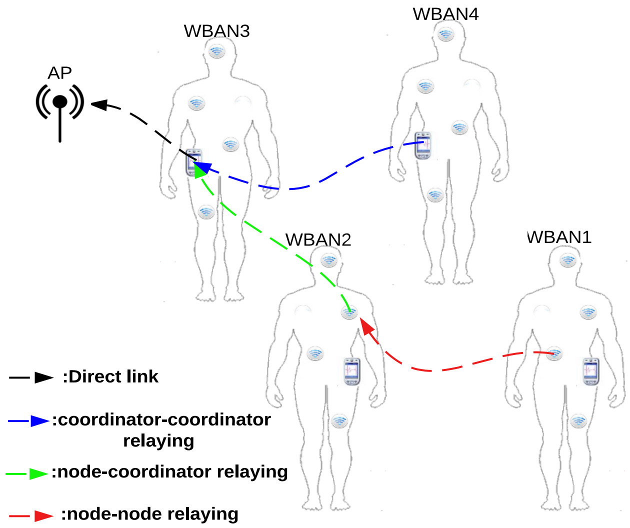


Figure 2.2 – Inter-WBANs communication

ation in case of connection loss or long distance with remote access points, coordinator-node cooperation in case the coordinator is unable to serve as a gateway for its sensor nodes because of its battery depletion, and finally node-node cooperation in the case of transmission incapability of neighbor coordinators. In this last case, coordinators' respective nodes shall cooperate as follows: a node of $WBAN_1$ has its coordinator power down and a node of $WBAN_2$ is in the same situation except that it can ask for help from the coordinator of $WBAN_3$ which is near and whose residual energy is enough for that service. Therefore, the node of $WBAN1$ can contact the node of $WBAN_2$ to convey its data to the coordinator of $WBAN_3$. When sensor nodes of different WBANs have to cooperate, their group must be composed of at least three WBANs.

Some protocols and algorithms have been proposed for intra-WBAN routing to increase throughput and network lifetime [23][64][11][81][3][16][43][93][81], but routing mechanisms for a group of WBANs by considering energy efficiency is so far not proposed. In this work, we have proposed a NetBAN routing solution to increase network lifetime and ensure data delivery taking into account the energy and connection issue. The OLSR [19] routing protocol has been modified to Energy Aware OLSR (EA-OLSR) by defining a new multipoint relays (MPRs) selection algorithm and a modified TC packet sending mechanism. The performances of OLSR protocol in terms of throughput, delay and network lifetime [76], have influenced the choice of this protocol and optimizing it to make it more energy efficient and adaptable to the NetBAN case.

2.2.1 EA-OLSR

The Energy Aware OLSR proposed in this work intends to increase the overall network lifetime by balancing consumed energy by each node with the length of the route. Thus, each node periodically calculates its lifetime using mainly residual energy and packet rate. Let $RLT_i(t)$ and $RE_i(t)$ be the remaining lifetime and the residual energy of a node i at instant t respectively. Then, $RLT_i(t)$ is given by the equation 2.3.

$$RLT_i(t) = \frac{RE_i(t)}{RE_i(t-1) - RE_i(t)} \tag{2.3}$$

There are two major contributions with EA-OLSR: new MPR selection algorithm and route building heuristic based on modified TC packet transmission. In fact, the RLT value is transmitted in the hello packet and used as parameter in MPR nodes election and route building process.

2.2.1.1 MPR election algorithm

Our new MPR election algorithm uses the remaining lifetime RLT of each coordinator to make choice of node forwarder by comparing with other coordinators' RLT values.

The principle to select the MPRs is: *choose the smallest set of one-hop neighbors having great remaining lifetime to cover all the two-hop neighbors.* In fact, if two coordinators have the same number of two-hop neighbors, the one with long lifetime will be chosen as depicted in Algorithm 1.

For more clarity before algorithms details, some notations and conventions are set and refer to those used in [13].

Considering a node i, let $N_1(i)$ be the 1-hop neighborhood of i, the group of nodes which are in i's transmission range and share a bidirectional link with i. Let $N_2(i)$ then be the 2-hop neighborhood of i, the group of nodes which are neighbors of at least one node of $N_1(i)$ but which do not belong to $N_1(i)$. i.e. $k \in N_2(i) \iff \exists j \in N_1(i) | k \in N_1(j) \wedge k \notin N_1(i)$.

Now, for a node $j \in N_1(i)$, let $d_i^+(j)$ be the number of nodes of $N_2(i)$ which are in $N_1(j)$ but not in $N_1(i)$. i.e. $d_i^+(j) = |N_2(i) \cap N_1(j)|$ and $N_i^1(j) = N_2(i) \cap N_1(j)$.

For a node $k \in N_2(i)$, let $d_i^-(k)$ be the number of nodes of $N_1(i)$ which are in $N_1(k)$: $d_i^-(k) = |N_1(i) \cap N_1(k)|$. It denotes the number of nodes in i's neighborhood that i can pass by to reach k. Accordingly, $N_i^2(k) = N_1(i) \cap N_1(k)$ denotes the set of nodes in i's neighborhood that i can pass by to reach k.

$RLT(i)$ and $w(i)$ are the remaining lifetime and the willingness of node i respectively.

Algorithm 1 : MPR selection algorithm with energy awareness

$\forall j \in N_1(i)$
if $w(j) = 0(WILL\_NEVER)$ **then**
    Remove j from $N_1(i)$
end if
    $\forall j \in N_1(i)$
if $\exists k \in N_i^1(k)|d_i^-(k) = 1$ **then**
    Add j in $MPR(i)$
    Remove j from $N_1(i)$ and $N_i^2(k)$ from $N_2(i)$
end if
while $N_2(u) \neq \emptyset$ **do**
    $\forall j \in N_1(i)|d_i^+(j) = max(d_i^+(s), \forall s \in N_2(i))$
    Add j in D
    if $|D| > 1$ & $\exists s \in D|RLT(s) = max(RLT(j), \forall j \in D)$ **then**
        Add s in $MPR(i)$
        Remove s from $N_1(i)$ and $N_i^2(k)$ from $N_2(i)$
    else
        Add j in $MPR(i)$
        Remove j from $N_1(i)$ and $N_i^2(k)$ from $N_2(i)$
    end if
end while

2.2.1.2 Route building algorithm

Regarding the route building, the way the TC packet is sent and processed is modified. In fact, unlike the classic OLSR where TC packet is generated by every node having been chosen as MPR and contains all its neighbor nodes, TC packet in EA-OLSR is generated by every node and is empty. Additionally, it contains a field of remaining lifetime as in hello packet. It is then broadcasted in the network and forwarded following the principle of MPR. Each node receiving the packet checks whether it is its generator or it passes by once again and discards it. If not, it shall use it to build the route between the originator and the receiver. It then adds its address, increments the counter and forwards it if it is chosen as an MPR by the sender (Algorithm 2).

At each coordinator receiving the TC packet, the routing table is built following the principle: *choose the shortest route with the most coordinator lifetime.* That to say, unlike the classic OLSR where the route is built according to the optimization of the number of hops, in EA-OLSR the route having the greatest lifetime sum of all involved coordinators will be considered.

2.2.2 Our NetBAN routing principles

Cooperative transmission shall occur in three communication levels, i.e. coordinator to coordinator, node to coordinator and node to node. In the general scenario, sensor nodes are connected to the coordinator and the coordinators are connected to a gateway in

Algorithm 2 : TC packet sending and route building

```
Receive TC packet
if I am its originator then
    Discard
else
    if the packet have already passed (T_seq > ANSN) then
        Discard
    else
        if there exists a route to its originator then
            Compare the new route's lifetime with the old one
            Record the route with maximum lifetime
        end if
    end if
end if
if I am an MPR of its sender then
    Append my address
    Forward the packet
end if
```

star topology way. The coordinator shall switch to ad-hoc configuration when it looses connection with the gateway and when its energy level reaches the *StopThreshold*. It shall not accept any relay transmission from other coordinators but rarely from sensor nodes. Thus, our NetBAN routing proposal consists of two main parts: the first part for node described in Algorithm 3 concerns the intra-WBAN routing and the second part for coordinator is related to the inter-WBANs and off-WBAN routing.

The first part consists in a *WBAN initialization*. This part is actually an intra WBAN routing mechanism that was first proposed in [11] and for which we add some details to make it working at routing layer. Thus, the coordinator broadcasts a *DISCOVERY* packet to discover its nodes. This DISCOVERY packet carries some informations such as *RE* and TTL. Upon receiving a DICOVERY packet with $TTL = 2$, a node understands that it is in direct link with the coordinator and decrements TTL by 1 before it rebroadcasts the packet. If a node receives the packet with $TTL = 1$ it does not forward it and sets the node it receives the DISCOVERY packet from as a relay to reach the coordinator. This first phase is only valid for the NetBAN while the following second phase can be used in any MANET for energy awareness.

The second part consists of 3 different states mutually exclusive. Each coordinator shall first communicate directly with an Access Point (AP) to deliver packets to a remote station using static routing, or shall second switch to ad-hoc mode using previously defined EA-OLSR, or finally leave its sensor nodes transmit their data themselves.

In fact, while there is no connection or energy issue, the coordinator transmits its packets while it is connected to the AP in star topology. It is for example, the case when a coordinator as a smartphone is connected to a WIFI AP. This state is likely to be optimal and the coordinator can easily serve for relaying.

Algorithm 3 : A node operating mode

Waiting for DISCOVERY packet while sensing
if Receive a DISCOVERY packet **then**
    if $DISCOVERY.TTL == 1$ **then**
        $NextHopAddress \leftarrow CoordinatorAddress$
        $NextHopRE \leftarrow DISCOVERY.RE$
        $SetDISCOVERY.TTL \leftarrow 1$
        $SetDISCOVERY.RE \leftarrow SelfRE$
        Broadcast DISCOVERY packet
    else
        if $NextHopAddress == NULL$ OR $NextHopRE < DISCOVERY.RE$ **then**
            $NextHopAddress \leftarrow SenderNodeAddress$
            Send response to the coordinator
        end if
    end if
    Define transmission path
end if
Send sensed or relayed data using defined path

When the connection to the AP breaks down, it switches to the second state using EA-OLSR by starting to send hello packets to its neighbors. The OLSR' hello packet is reformatted in EA-OLSR to carry out additional necessary information such as Remaining Lifetime RLT. Hence, the *Reserved* field is divided into two parts: one part remains *Reserved* and the other part as RLT. As the inter-WBAN communication intends to occur in applications with either a very low or high mobility such as elders at retirement home or athletes in sport training, the HELLO packet is periodically exchanged after a hello period *HelloInterval* and this period is determined according to some factors. In fact, given *lowMobSpeed* for low mobility speed and *highMobSpeed* for high mobility speed, average mobility is *mobSpeed* given by Equation 2.4.

$$mobSpeed = (highMobSpeed + lowMobSpeed)/2 \tag{2.4}$$

Moreover, for a coordinator with a transmission coverage radius *coverage*, the Hello period is given by the Equation 2.5.

$$HelloInterval = \frac{coverage}{mobSpeed} \tag{2.5}$$

Every time the MPR table values change, the TC packet will be sent and the routing table shall be updated at the receiver.

During these two first states, the coordinator shall set willingness filed to WILL_LOW if its residual energy level reaches the *StopThreshold*. In this way, it would save energy by not acting as relay to other coordinators. However, it shall relay packets of sensor nodes whose coordinator is no longer operating.

The final state occurs when the residual energy level reaches the *LeaveThreshold*. In this way, the coordinator has to inform its sensor nodes about its incapability for serving as a gateway. In fact, each coordinator normally collects data from its sensor nodes and conveys them to the remote station and periodically checks its *RE*. As the coordinator updates and keeps in its routing table the information relating to the residual energy of its neighboring coordinators, when its *RE* has reached the threshold *LeaveThreshold*, it informs its nodes by locally broadcasting in the whole WBAN a LEAVE packet containing possible routes before it ceases its services. A LEAVE packet could contain the route to the nearest coordinator with enough energy to convey data.

2.2.3 Simulation and discussion

Performance evaluation through simulation of our proposal has been made. As illustrated by the chosen scenario in Figure 2.3., 25 nodes have been used including one of them taken as the main AP and 24 other remaining nodes forming 8 WBANs with 2 sensor nodes and a coordinator each.

```
19    20        21    22        23    24
 \    /          \    /          \    /
  \  /            \  /            \  /
   6-------------7-------------8
   |               |               |
   |               |               |
13 |  14        15 |  16        17 |  18
 \ |  /          \ |  /          \ |  /
  \|/             \|/             \|/
   3-------------4-------------5
   |               |               |
   |               |               |
   |            9  |  10        11 |  12
   |             \ |  /          \ |  /
   |              \|/             \|/
   0-------------1-------------2
```

Figure 2.3 – Simulation topology

To study the effects of battery depletion and connection failure, two configurations are considered. In the first configuration, all nodes and coordinators are static so as to study only the behavior of the network according to the energy consumption. The second configuration, however, includes mobility factor where each WBAN (a coordinator with its nodes) moves to allow the possibility of connection failure. In both configurations, only sensor nodes generate and transmit packets to the AP through their coordinators. Thus, the sensor nodes in a WBAN send their packets to the coordinator using static routing till the moment they receive the LEAVE packet. The coordinators however use EA-OLSR to route packets to the AP.

The performances of EA-OLSR were compared to those of classic OLSR without energy optimization but also to those of another existing energy optimisation OLSR in literature called EE-OLSR [22]. The network lifetime, average energy consumption per coordinator and data delivery rate are the considered simulation metrics. The obtained results show that EA-OLSR proposal is really energy efficient and outperforms the two other protocols. It is also noticed that with EA-OLSR, the energy consumption tends to get uniformly distributed on all coordinator nodes in the network which results in significant improvement in network lifetime.

2.3 Intra-WBAN MAC cooperation

Publications : [37]

As discussed in section 2.1, the IEEE 802.15.6 standard [2] defines an optional two-hop cooperative WBAN communication to overcome the attenuation factor issue around the human body. However, there is no specification in the standard on the way the network is initialized when operating in two-hop topology to offer some Quality of Service (QoS) parameters, ensure the coverage of all nodes and reducing the energy consumption. Several studies on the importance of setting two-hop topology mainly for the coexistence of many WBANs have been explored in the literature. It was shown that this two-hop topology improves better co-channel interference mitigation between WBANs than the single-hop topology [38][39][37][20][72][67][24]. Moreover, various energy efficient MAC approaches to satisfy WBANs requirements such as guaranteed QoS, multiple physical layer support and adaptability to traffic variations have been proposed [29][52][91].

However, no works on the two-hop topology for intra-WBAN communication have so far taken into consideration for transmissions flow optimization. Indeed, few authors if any studied the possibility to enhance data flow or evaluate transmission performance of WBAN cooperation while keeping energy optimization, what this work focuses on. In the purpose of optimizing the energy consumption in the specific scope of two-hop intra-WBAN communication, we review some QoS parameters and propose a cooperative relaying mechanism based on MAC protocol. This mechanism merges data at the relaying node to increase data exchange without overloading the whole network flow with control packets. In addition, we propose an algorithm for the initialization phase when a two-hop topology is applied.

2.3.1 IEEE 802.15.6 MAC Overview

Since our proposal falls into cooperation and relaying of frames at MAC layer, this section mainly highlights the network topology and the MAC frame formatting in a WBAN as described in the IEEE 802.15.6 standard. In fact, a WBAN is composed of one and only one hub as a coordinator and up to 64 nodes deployed in one-hop star topology or in two-hop extended topology. Exchanged frames over the network are classified into three categories: Management, Control and Data frames. The medium access is controlled according to traffic classes (TCs) defined as follows: background traffic (TC0), best effort traffic (TC1), excellent effort traffic (TC2), controlled load (TC3), video (TC4), voice (TC5), media data or network control traffic (TC6) and emergency or medical event reports (TC7). The MAC Frames consist of fixed-length MAC header, the Frame Check Sequence (FCS) and a variable-length MAC frame body as illustrated in Fig. 2.4. Finally, in the two-hop extension topology, it is stipulated that a relayed MAC Frame has to be encapsulated in a relaying MAC Frame as formatted in Fig. 2.5. This way of encapsulation reduces the space of payload data given the redundance of some header fields of the encapsulated frames in the resulting frame.

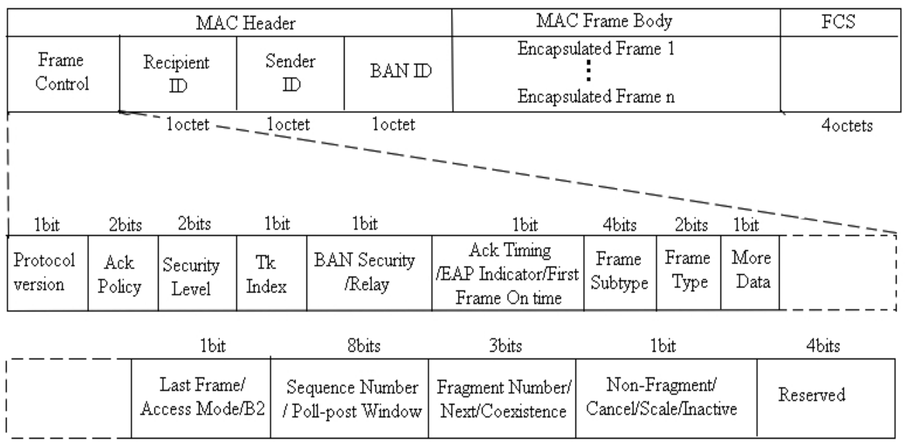


Figure 2.4 – IEEE 802.15.6 MAC Frame format

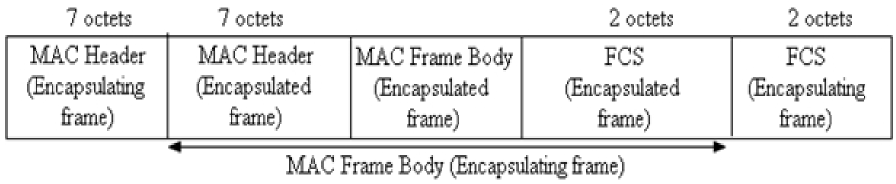


Figure 2.5 – General IEEE 802.15.6 frame encapsulation format

2.3.2 Proposed approach

In this work we propose a new approach of encapsulation at the relay node. This approach falls into cooperation and relaying and based on two main ideas: resizing MAC frame format defined by the standard to gain space and increase data flow, and merging frames from relayed nodes into one at relay node to reduce transmission flow and therefore increase data transmission rate while optimizing energy consumption.

2.3.2.1 MAC Frame reformatting

As observations from the MAC formatting described in Section 2.3.1, there is redundancy of information in some fields such as BAN ID, Receipt ID, Sender ID, Reserved, etc. Furthermore, a frame of 255 bytes of frame body and 9 bytes of frame header is too long for physiological data like temperature, glycemic level, heartbeat, etc. except the case of multimedia data. Therefore we propose to merge bit per bit frames from the relayed nodes into a single frame at a relaying node before getting to the hub. This merging operation is like interleaving operation with uniform interleaver and benefits for instance from burst error correcting advantages. Thus, when a node set as relay receives a packet to relay, it checks its integrity using the FCS field and removes some unnecessary fields. If it is not in the transmission schedule, it pushes it into the buffer stack. However, if it is possible to send, it checks whether the packet is urgent or the buffer is empty. If so, it encapsulates and sends it straightway. If not, it merges it with buffer packets and sets MEN (Merged Frames Number) field of the resultant frame with the number of merged frames before it sends it. The merging process is done as follows: Given m MAC frames $R_1, \ldots, R_i \ldots, R_m$ of length n each, and whose bits are ordered as $R_i = b_{i1}, \ldots, b_{in}$, the coded relayed MAC frame body after merging is set as follows: $R = B_1, \ldots, B_j, \ldots, B_n$ where $B_j = b_{1j}, \ldots, b_{ij}, \ldots, b_{mj}$
Example: $m = 2, n = 8$
$R_1 : \underbrace{0}_{b_{11}}1001100 \quad and \quad R_2 : \underbrace{1}_{b_{21}}0101010$
$R : \underbrace{01}_{B_1=b_{11}b_{21}} \quad 10010011100100$

This process follows some principles and assumptions:

1. The Frames to be merged must be from the closest traffic type or have the same user priority (UP) if this latter is above 4. Furthermore, they must not exceed 255 bytes long if merged. For our simulations we considered all frames as being from the same traffic type and same user priority.

2. For data packets, the relaying is only ascending, i.e. from nodes to the hub and for INIT packet, the relaying is only descending, i.e. from the hub to nodes.

This phase is depicted in figure 2.6 and summarized in the algorithm 4.

2.3.2.2 Frame transmission scheme

We propose a MAC layer routing technique where each node can reach a hub and vice versa, in at most two hops. As depicted in algorithm 5, by using the IEEE 802.15.6 MAC frame format, a hub broadcasts an initialization beacon to discover the nodes by setting Relay field to 0. To define this initialization beacon we used a reserved field in MAC Frame Control as a management subtype with Frame Subtype value of **0111**

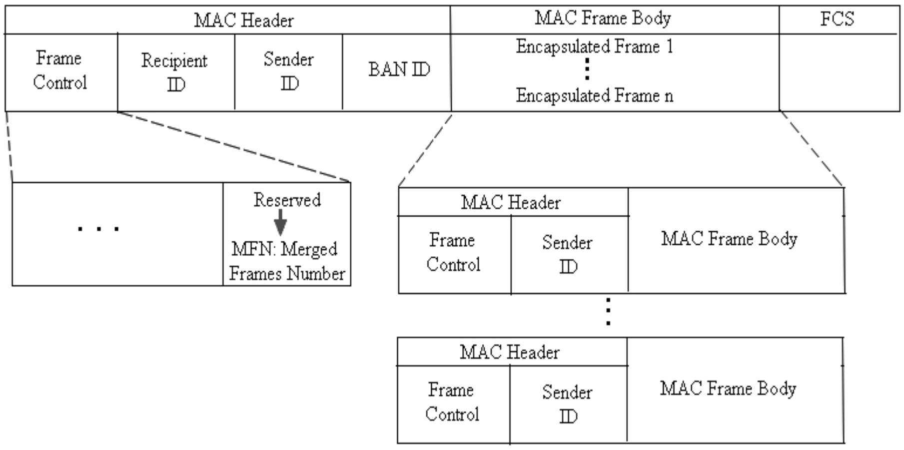


Figure 2.6 – General merged frame encapsulation format

Algorithm 4 : Decode and Merge

if a node receives a packet **then**
    Check packet integrity with FCS and Decode
    Drop useless fields: Recipient ID, BAN ID, FCS
    if Received Packet is not Emergency AND Buffer is not empty **then**
        Merge packets (received packet with buffer packets)
        Encapsulate
    else
        Encapsulate
    end if
    Send packet
end if

and **INIT** as Frame subtype name. When a node receives an INIT beacon with Relay field set to 0, it understands that it is at 1-hop from the hub and therefore uses it and forwards it after setting SenderAddress to its ID and Relay field to 1. When a node receives an INIT beacon with Relay field set 1, it understands that it is at 2-hops from the hub and discards it. If it has previously received an INIT beacon, it keeps the best link to the source for its subsequent transmissions using LQI (Link Quality Indicator).

Algorithm 6 summarizes the relaying capability of a node. if a node finds it is capable of relaying, it sets Relay field to 1 and broadcasts a beacon to notify others. The relaying capability is calculated taking into account the amount of frames in the buffer, the energy and the link quality according to the formula expressed by Eq. 2.6 and Eq. 2.7. Thus, a node is capable of relaying when:

$$FE > 0 \quad AND \quad LQI > TV \tag{2.6}$$

$$where \quad FE = RE - 8 \times Pn \times Fs \times Eb - TE \tag{2.7}$$

Algorithm 5 : Initialization phase

```
The Hub broadcasts an INIT beacon with Relay ← 0
if a node receives an INIT beacon then
    if Relay == 0 and is the first then
        Use it
        Relay it with Relay ← 1 and SenderAddress ← NodeID
    else
        if Is the first then
            Use it
        else
            if the previous has Relay == 0 then
                Discard it
            else
                Compare its LQI with the LQI of the previous
                Choose the best link, i.e. the Relay Node
                Use the choosen
            end if
        end if
    end if
end if
```

With FE the Functional Energy that allows a node to relay; RE the Residual Energy left in the battery; TE the Threshold Energy representing the minimum energy that allows to send SOS message; Pn the Packet number representing the number of packets in the buffer; Fs the MAC Frame size (bytes); Eb the Energy per bit representing the energy consumed by a bit sent what is on average 10PJ [14]; and TV the LQI Threshold Value ranging from 0 to 255 as defined in the IEEE 802.15.4 standard [1]. It was shown in [28] that a link quality indicator (LQI) value of 105 or beyond corresponds to maximum of link delivery ratio in IEEE 802.15.4 standard.

When a node receives a beacon with Relay field set to 1 from another node with a better link than the one it is connected to, it sets it as its new relay by sending a connection request. When a node is a relay it uses algorithm 4 to send data to the hub.

2.3.3 Simulation and discussion

Considering the top part of the WBAN depicted by Fig. 2.7.a, if the two-hop topology is set as defined in the standard, the relay node R will have to transmit 3 frames as illustrated by Fig. 2.7.b if it has data to transmit too. However, as shown by Fig. 2.7.c, if Decode and Merge Cooperation is applied, only one transmission will be required.

Algorithm 6 : Cooperation and Relaying

if a node is capable of relaying **then**
    Relay ← 1
    Broadcast a beacon
end if
if a node receives a beacon with *Relay* == 1 from best link **then**
    Connection Request
    Transmit data to Relay
end if
if a node is Relay AND Receives Connection Request **then**
    Connection Assignment
    Algorithm 4
end if

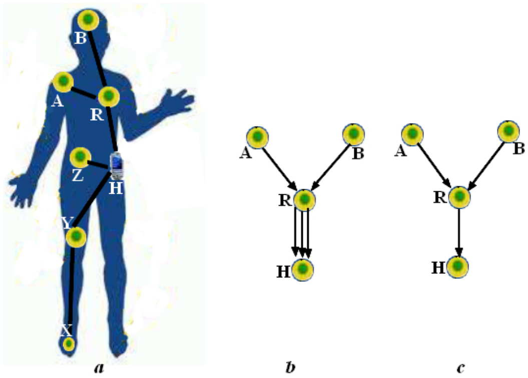


Figure 2.7 – WBAN 2-hop topology transmission models

In other words, let us take N the number of relayed nodes and r the number of relays. If all the nodes (relayed and relay nodes) have packets to transmit, $N+r$ packets will be delivered to the hub in $2N+r$ transmissions for normal WBAN defined in the standard while the same amount of packets will take only $N+r$ transmissions when using our Decode and Merge technique. Therefore, if $N+r$ packets require $2N+r$ transmissions and T time for the WBAN model defined by the standard, $N+r+N-r=2N$ packets will be delivered when using Decode and Merge in the same time T, that to say a gain of $N-r$. By generalizing previous results, we have:

-$Packets = PR * T * \sum_{i=1}^{N+r} Node_i$ without Decode and Merge;
-$Packets = PR * T * \sum_{i=1}^{2N} Node_i$ with Decode and Merge;
-$Gain = \frac{\sum_{i=1}^{N-r} Node_i}{\sum_{i=1}^{N+r} Node_i}$ what gives about 20% in our case.

Where PR is the packet rate.

Moreover, we conducted some simulation while considering some performance evaluation criteria such as general throughput (exchanged packets), energy consumption and transmission quality as interference variation. By exchanged packets we mean the amount of both transmitted and received packets including control, management and data packets. In addition, transmission quality refers to either success or failure of packets transmission due to collision, low sensitivity or interference. However, due to the constraints of simulation, we chose relay nodes before the simulation start. The obtained results show how our solution outperforms the standard model. Indeed, simulation results showed that our proposal increases general throughput and specially the amount of data packets delivered to the hub. Moreover, the ability of transmission in interference conditions has increased. It was also shown that the energy consumption has been optimized.

2.4 QoS scheduling in WBANs

Publications : [32]

Health monitoring systems (HMS) should implement Quality of Service (QoS) tools to ensure a certain quality level especially in terms of delay and packet loss as related applications require a very low or no data loss or waiting time for transmissions. As a WBAN deals with eight classes of data, healthcare applications offer much privilege to some classes such as emergency, high-priority and medical data over other classes. However, there is so far no mechanisms defined to sustain healthcare applications requirements in terms of time-sensitivity at the coordinator from WBAN to peer-networks, despite of some mechanisms set within the WBAN to guarantee QoS according to data requirements. Indeed, peer-networks (WIFI, LTE, WIMAX, etc.) have their own policies to schedule data but the bottom order should influence the top one. Existing coordinators (PDA, smartphones, ...) do not support yet these requirements properly. Therefore, there is a real need to link QoS parameters from the WBAN which is a source of data to peer-networks that stand for data delivery to data processing station.

Based on the standard IEEE 802.15.6 [2], this work suggests to implement a scheduling technique at the coordinator to mitigate the waiting time for emergency and medical data. Many scheduling strategies such as Weighted Fair Queuing (WFQ), Low Latency Queuing (LLQ), Priority Weighted Round Robin (PWRR), etc.[54][80] have been proposed in literature. However, PWRR strategy is likely to meet the requirements at this stage. In fact, PWRR is a concatenation of Priority Scheduling (PS) and Weighted Round Robin (WRR) strategies. In our case, a very high priority flow is scheduled using PS and other flows are scheduled using WRR. At the end, either the very high priority flow or the output of WRR is served. For its simplicity in implementation even in hardware, it can be applied to high speed infrastructures in the core and edge of networks. Y. Zhang et al. [34] analytically evaluated the PWRR for Assured Forwarding packets class using a queuing model for DiffServ architecture. This latter has besides been adapted for our proposal. In the same way, Vladimir H. et al. [90] proposed a mathematical model of WRR strategy to manage congestion in converged packet networks. These works help to understand the usefulness of scheduling strategy based on round robin.

2.4.1 Model description

In a WBAN, data traffic from sensor nodes to the coordinator access the medium according to the priority model following the Eq. 2.8. In that, for a node with a data priority UP_i, the value of the backoff counter is initialized to a random integer from $[1, W_0^i]$, where $[W_0^i]$ denotes the minimum value of the backoff counter. For every number of retry, the value of the contention window is computed depending on whether it is odd or even.

$$W_k^i = \begin{cases} W_0^i & \text{when } k = 0 \\ W_k^{i-1} & \text{when } l\ is\ odd, 1 \leq k \leq m \\ min(2W_k^{i-1}, W_{max}^i) & \text{when } k\ is\ even, 2 \leq k \leq m \end{cases} \tag{2.8}$$

Where l stands for the number of retries of transmission that a data packet has undergone.

When data get to the coordinator, they are put into buffers and scheduled in the way to provide for a minimum waiting time for service to time-sensitive data and for real-time applications. As data arriving at the coordinator from sensor nodes are classified into eight traffic classes as user priorities (UPs) and given that some traffic classes are not related to healthcare applications, especially those with low priorities, they are then mapped into only four priority classes Ps following the Eq. 2.9.

$$P_i = \begin{cases} \frac{UP_i}{2} \times 2 + 1 & \text{when } UP_i \geq 5 \\ \frac{UP_i - 2}{2} \times 2 + 1 & \text{when } UP_i < 5 \end{cases} \tag{2.9}$$

In this way, data crossing the coordinator should be classified into Emergency (EM), Medical (MD), Audio-Video (AV) and non-Medical (nMD). The mapping function between data class and data priority is as follows:
$(P_1, P_2, P_3, P_4) = (EM, MD, AV, nMD)$ with $(P_1, P_2, P_3, P_4) = (7, 5, 3, 1)$

The incoming data will then be sent to four different buffers after the mapping stage and each buffer has the same weight as the priority of the traffic class it receives, i.e. Q_1 with weight 7 contains EM, Q_2 with weight 5 contains MD, Q_3 with weight 3 contains AV, and Q_4 with weight 1 contains nMD.

Data flow from Q_1 and WRR outgoing flow are scheduled using priority scheduling while those from Q_2, Q_3 and Q_4 are scheduled using WRR.

The architecture illustrated in Fig. 2.8 offers advantages to emergency flows to keep their priority in PS and then do not have to wait. Medical flows are managed in separated queue from the one of emergency flows what gives them high priority over other flows and they are not penalized in PS if emergency data arrive while they are under service because the PS runs in non-preemptive mode. The architecture finally prevents other data flows from starvation.

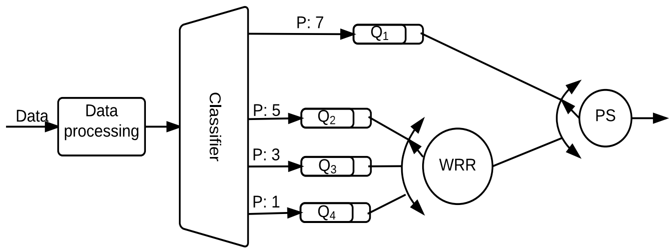


Figure 2.8 – A PWRR architecture for a WBAN based HMS

2.4.2 Priority Weighted Round Robin (PWRR)

The WRR scheduling algorithm is simply RR with weights assigned to each queue. Unlike the RR whose transmission service cycles through queues taking equal amount of packets (one packet) from each, the WRR service takes amount of packets as per the weight assigned to each queue. Hence, the WRR uses the priority as weights. It also ensures that lower priority queues never starved for long time for buffer space and output link bandwidth. The WRR scheduling is based on assigning fraction weight φ_i to each service queue such that the sum of weight of all service queues is equal to one.

$$\sum_{i=1}^{n} \varphi_i = 1 \tag{2.10}$$

As it is already stated in the introduction section and illustrated in Fig. 2.8, the PWRR scheduling is a combination of priority scheduling (PS) and WRR strategies. In this case of WBAN based HMS, the emergency data are scheduled by non-preemptive PS with the WRR output data. Other data, including medical data, are scheduled by WRR and pass to PS afterwards.

As the main goal here is to guarantee the minimum waiting time and also the delay for emergency and medical data, the evaluation is done by comparing PWRR with

FIFO strategy.

By applying the queuing theory of a M/G/1 system with n priorities, i.e. with multiple classes of data, let us assume that the data flows arrive according to the Poisson process with rate λ_i (i=1, 2, , n), that to say that the inter-arrival times are independent and exponentially distributed random variables with parameter λ. The service times are also assumed to be independent and exponentially distributed with parameter μ. Furthermore, all the involved random variables are supposed to be independent of each other.

2.4.2.1 First stage: PS

As illustrated in Fig. 2.8 and stated before, we have two scheduling techniques WRR and non-preemptive PS. For the PS we consider two flows: the emergency class (the highest priority) and the flow from the second stage.

The system stability is given by

$$\sum_{i=1}^{n} \rho_i < 1 \tag{2.11}$$

Where $\rho_i = ^{\lambda_i} /_{\mu_i}, i = 1, 2, ...$ and n is the number of queues.

Let $E(W_i)$, $E(D_i)$, $E(N_i)$ and $E(R)$ be the mean response time, the mean delay, the mean number of class i in the system and the mean residual service time, respectively. The delay of a data flow i is simply the time it spends waiting for the server to be free if it is being used and the time of its own service. As the service times are exponentially distributed with parameter μ, the delay is given by

$$E(D_i) = E(W_i) + \frac{1}{\mu_i} \tag{2.12}$$

Assuming that the priority i is higher than $i + 1$, we get by the Pollaczek Khintchine Formula for the high priority class:

$E(W_1) = E(R) + \frac{E(N_1)}{\mu_1}$ what gives, by Little's law

$$E(W_1) = \frac{E(R)}{(1 - \rho_1)} \tag{2.13}$$

Given that,

$$\sum_{i=1}^{n} N_i = \frac{\sum_{i=1}^{n} \rho_i}{(1 - \sum_{i=1}^{n} \rho_i)} \tag{2.14}$$

By generalization and using the Little's law, we get

$$E(W_i) = \frac{E(N_i)}{\lambda_i} = \frac{E(R)}{(1 - \sum_{j=1}^{i-1} \rho_j)(1 - \sum_{j=1}^{i} \rho_1)} \tag{2.15}$$

$E(R) = \frac{1}{1} \sum_{i=1}^{n} \lambda_i E(S_i^2)$
$\Leftrightarrow E(R) = \frac{1}{2} \sum_{i=1}^{n} \lambda_i \frac{1}{\mu_i^2}$, with $E(S_i) = \frac{1}{\mu_i}$
$\Leftrightarrow E(R) = \frac{1}{2} \sum_{i=1}^{n} \frac{\rho_i}{\mu_i}$, with $\rho_i = \frac{\lambda_i}{\mu_i}$

$$\Rightarrow E(W_i) = \frac{\frac{1}{2} \sum_{j=1}^{n} \frac{\rho_j}{\mu_j}}{(1 - \sum_{j=1}^{i-1} \rho_j)(1 - \sum_{j=1}^{i} \rho_i)} \tag{2.16}$$

When using FIFO strategy, $E(W) = \frac{E(N)}{\sum_{i=1}^{n} \lambda_i}$

$\Rightarrow E(W) = \frac{\sum_{i=1}^{n} \rho_i}{(1 - \sum_{i=1}^{n} \rho_i)(\sum_{i=1}^{n} \lambda_i)}$

With relations (2.11) and $\rho_i =^{\lambda_i} /_{\mu_i}$, we get

$$E(W) = \frac{1}{(1 - \sum_{i=1}^{n} \rho_i)} \tag{2.17}$$

Relations (2.13) and (2.17) are such that $E_{PS}(W_1) < E_{FIFO}(W_i)$

2.4.2.2 Second stage: WRR+PS

In the second stage of PWRR architecture the data of buffer i wait for $1 - \varphi_i$ units of time before their service as buffers are served in cycle way in respect of assigned weights. In this way Eq. 2.16 becomes:

$$\Rightarrow E(W_i) = \frac{\frac{1}{2}(1 - \varphi_i) \sum_{j=1}^{n} \frac{\rho_j}{\mu_j}}{(1 - \sum_{j=1}^{i-1} \rho_j)(1 - \sum_{j=1}^{i} \rho_j)} \tag{2.18}$$

In addition, the output of WRR becomes the second priority in PS with the probability B_{em} by which the emergency data as first priority can be in the server. The second priority in PS is given by

$$E(W_2) = frac(\frac{1}{2} \sum_{j=1}^{n} \frac{\rho_j}{\mu_j})(1 - \rho_1)(1 - \sum_{j=1}^{2} \rho_j) \tag{2.19}$$

Finally, the waiting time and delay become respectively:

$$E(W_i) = \frac{\frac{1}{2}(1-\varphi_i)\sum_{j=1}^{n}\frac{\rho_j}{\mu_j}}{(1-\sum_{j=1}^{i-1}\rho_j)(1-\sum_{j=1}^{i}\rho_j)} + \frac{\frac{1}{2}B_{em}\sum_{j=1}^{n}\frac{\rho_j}{\mu_j}}{(1-\rho_1)(1-\sum_{j=1}^{2}\rho_j)} \tag{2.20}$$

$$E(D_i) = \frac{\frac{1}{2}(1-\varphi_i)\sum_{j=1}^{n}\frac{\rho_j}{\mu_j}}{(1-\sum_{j=1}^{i-1}\rho_j)(1-\sum_{j=1}^{i}\rho_j)} + \frac{\frac{1}{2}B_{em}\sum_{j=1}^{n}\frac{\rho_j}{\mu_j}}{(1-\rho_1)(1-\sum_{j=1}^{2}\rho_j)} + \frac{1}{\mu_i} \tag{2.21}$$

Assuming that all types of data in the WBAN have the same probability to occur, the emergency data would be generated with the probability of $B_{em} = 1/8$, given that there are eight different UPs corresponding to different types of data.

2.4.3 Simulation and discussion

As we are interested in the delay evaluation of the high priority data or time-sensitive data, we take much attention only on emergency and medical data with UPs 7 and 5 respectively. In reality, emergency data flows are not frequently generated what could lead to assume that the high priority has low arrival rate; however here we take the worst case where EM flows have as important arrival rate as other flows and then assume that all sensor nodes have the same transmission rate and the same service rate $\mu = 1$ as the coordinator is the same server for all nodes. Thence, we vary the arrival rate of emergency flows, then one of the second priority flows and finally those of both flows: from $\sum_{i=1}^{n}\lambda = 0.1$ to $\sum_{i=1}^{n}\frac{\lambda_i}{\mu_i} < 1$ is still respected; this requirement is stated in condition 2.11. Simulation results for peer-networks involved in a WBAN based HMS show that, if PWRR is set, the behavior of WIFI, WIMAX and LTE networks remains the same in keeping all flows as per their priorities by mitigating the end-to-end delay. Moreover, it was shown that the increase of the arrival rate of emergency flows increases the delay of these latter too whereas the emergency flows have low arrival rate though in reality. It was also noticed that all data flows have lower delay in PWRR than in FIFO except the nMD flow whose delay increases if its arrival rate exceeds 0.45, hence the importance of considering the transmission rate of all involved flows. Ultimately, the WBAN based HMS should implement a scheduling mechanism at the coordinator and the PWRR seems to be the better candidate.

Chapter 3

LARGE SCALE WIRELESS SENSOR NETWORKS

Mobile sink based data gathering algorithms offer better energy distribution in the network and thus relatively longer network lifetimes. However, traffic control overhead is increased as the sink now has to update network about its changing position to ensure connectivity to the network. Mobile sink based data dissemination algorithms proposed in literature can be broadly classified into two main categories; Backbone-based routing structures and Tree-based routing structures. In Backbone-based structures, nodes organize themselves into either clusters or virtual grids where mostly only one cluster head (CH) per cluster is responsible for data aggregation and query forwarding [83][25][57][88][6][65][46][89][58]. Cluster-based routing mechanisms are scalable but require periodic communication to distribute cluster head (CH) role among nodes.

Tree-based dissemination structures, however, could be either source-based or sink-based structures. With source-based structures, event detecting node broadcasts event's information to the network and creates a tree-rooted at itself, and then, the sink uses this tree to retrieve data from the source. Source-based tree makes routing structure independent of the sink mobility as sink may use any tree branch to demand data from the source. It requires one tree formation per source-node making this mechanism infeasible for applications which have large number of sources. Contrarily, in sink-based structures sink broadcasts its location to the network which creates a tree rooted at the sink and then, nodes use the reverse tree path to deliver data to the sink. Sink-rooted routing mechanisms have relatively lower routing structure creation overhead as they require only one tree for per sink, irrespective of the number of sources. However, sink mobility necessitates periodic location updates to the network [85][42][68][86].

This chapter summarizes two sink-rooted energy-efficient routing algorithms we have proposed for large scale mobile sink WSNs. The first algorithm named SN-MPR is suitable for delay sensitive applications. The second algorithm named Duty-Cycle SN-MPR is a modified version of SN-MPR and suitable for delay tolerant applications. These two contributions are done within the PhD thesis of *Yasir Faheem.*

3.1 SN-MPR routing protocol for mobile sink WSNs

Publications : [26][46][47][49]
A distributive energy-efficient sink location update algorithm named Sensor Network Multi-Point Relay (SN-MPR) for WSN applications where sink is continuously mobile is proposed. The proposed SN-MPR algorithm combines several mechanisms in order to minimize sink location update overhead while maintaining continuous sensors-to-sink connectivity. With a mobile sink based WSN, sensors are not aware about sink location, and therefore, periodic broadcast is needed to update the network about the changing paths in order to ensure sensors-sink data dissemination. In our proposal, we used the Multi-Point Relay (MPR) forwarding [70] for sink location updates and queries. The proposed MPR based mechanism has been combined with a path local-repair technique which allow nodes to dynamically limit the scope of sink location update messages to only those nodes which are affected by sink's mobility; nodes for which routes towards the sink do not change due to sink mobility do not receive this message. Moreover, in order to reduce the data loss due to unstable links between mobile sink and its current neighbors, we propose a preemptive buffering technique where sink's neighbors act as temporary data collecting buffers when sink moves out of their transmission range.

3.1.1 Multi-Point Relay Broadcast

Our proposal uses MPR broadcast mechanism proposed by Qayyum et. al. for mobile ad hoc networks [70]. With MPRs, nodes exchange *hello* messages periodically, and a *hello* generated by a node n_i contains source's address, its willingness to be chosen as MPR, already discovered neighbors list and their link statuses (unspecified, asymmetric, symmetric, lost). Exchange of *hellos* enables every node to obtain information about its 1-hop and 2-hop neighbors, referred to as n_{i_1} and n_{i_2} respectively. Once, n_i has discovered its 1-hop and 2-hop neighbors, it chooses a minimum subset among its n_{i_1} neighbors, such that node n_i can access all its 2-hop neighbors i.e. n_{i_2} via this subset. These minimum number of 1-hop neighbors are referred to as MPRs of node n_i. This set of MPRs is changing over the time since MPRs consume more energy than non-MPRs, as they act as relays in addition to forwarding their own data. To distribute this role among nodes, we use the *willingness* field described in [19]. Once the battery level of a node n_i falls below a certain threshold, it lowers its *willingness* value and transmits it in a *hello* message. Neighbors after receiving this *hello* observe the lowered *willingness* of n_i, and locally exchange few *hellos*. This helps in balancing the power consumption in the network as nodes reselect MPRs with higher residual energies.

3.1.2 Neighbor Discovery

Neighbor discovery mechanism of SN-MPR is the same as that of MPR algorithm, however, *hellos* are not exchanged periodically through out the network lifetime. The exchange of *hellos* in SN-MPR happens only during the network initialization phase then afterwards between the mobile sink and its current neighbor nodes. The SN-MPR's neighborhood discovery process can be divided into two categories; static sensor-to-sensor neighbor discovery and mobile sink-to-sensor neighbor discovery.

3.1.2.1 Sensors Neighborhood Discovery

This is executed at the network initialization phase as sensors remain static after deployment. Once configured, there is no need to send periodic control packets. Newly deployed nodes start exchanging *hello* packets with 2 seconds interval. With every new *hello* message reception, new neighbors and/or their link information is updated. The exchange of *hello* messages is stopped once no more changes are detected in already discovered neighbors and their links after certain number of *hello* exchanges. At the end of the neighbor discovery process, an efficient MPR based virtual relay topology is in place. Afterwards, nodes will transmit *hellos* only under certain conditions.

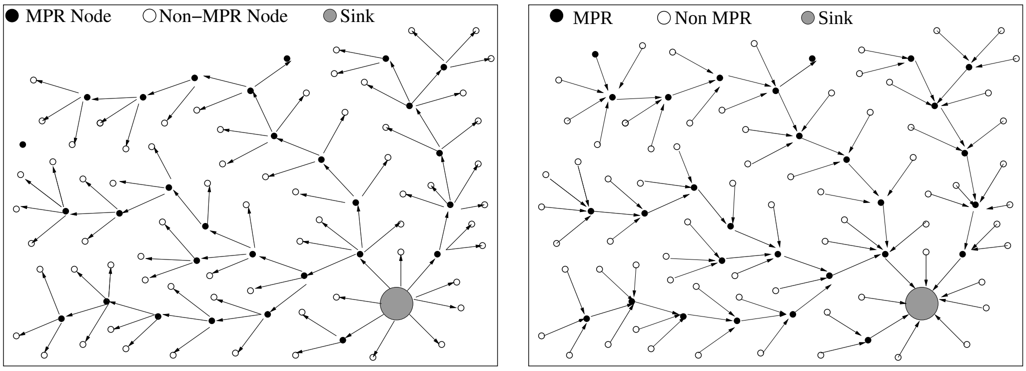
3.1.2.2 Sink Neighborhood Discovery

The mobile sink enters the network once the sensors' neighbor discovery process has converged. The sink transmits *hello* messages every 2 seconds. A node after receiving a *hello* message verifies the ID of the sender. If sink is the source of the *hello* message, it replies to the sink with a *hello* packet. This updates the links between sink and its current neighbors. Note that nodes transmit *hello* packets only in response to sink's *hello* message. Periodic *hello* transmission does not occur as sensors' neighborhood discovery has already converged. This enables the sink to discover new neighborhood as it changes its positions. Sink and its neighbors delete their respective entries when they can no longer hear each other after SINK_NEIGB_HOLD_TIMEOUT of 2×hello_interval.

3.1.3 Sink Location Updates and Reverse Tree Formation

The sink broadcasts location update messages periodically to reconfigure changing paths and to transmit queries. Here, we refer to these as Sink Location Update messages (SLU). A SLU message contains the ID of the sink, and if required, the sink may also append its queries in this message. As depicted in Figure-3.1a, when sink broadcasts a SLU packet to the whole network, only a limited number of MPR nodes (dotted black) rebroadcast the message whereas majority of non-MPR nodes (dotted white) receive the SLU message but do not forward it.

Once a SLU message is received by every node in the network through MPR broadcast mechanism, every node n_i chooses as its next-hop relay node towards the sink, referred to here as $next\_hop_{sink}$, the neighbor from which SLU message is received. Naturally, sink's all one-hop neighbors will select their respective next hop relay as sink i.e. $next\_hop_{sink}$ = *sink address*, since the SLU is received directly from the sink. However, its two-hop neighbors ($sink_{2\_hop}$) and nodes beyond may receive multiple copies of SLU message from different neighbors due to transmissions and queuing delays. In order to construct the reverse shortest-path sink-rooted tree, SLU receiving node should select as its next hop towards the sink the neighbor from which the SLU is received with minimum hop count. This can be determined from Time To Live (TTL) value contained in SLU's packet header. Thus, the reverse MPR path creates a reverse routing tree which is rooted at sink (Figure 3.1b).



(a) Sink location Dissemination (b) Sensors→Sink tree with sink as root

Figure 3.1 – SN-MPR location dissemination and path configuration mechanism

3.1.4 Local Repair and Preemptive Buffering

For a limited time interval, sink mobility affects only a limited network area. Thus, it may not be necessary to forward sink's SLU message to the whole network. We introduce a distributed local repair mechanism, whereby, MPR nodes dynamically decide whether to rebroadcast incoming SLU packets or not. We refer to two consecutive SLU messages as; SLU_{old} and SLU_{new}. The scope of the SLU$_{new}$ message depends upon sink's speed and direction. Suppose a *node* n_i had established $next\_hop_{sink} = n_j$ on the basis of the previous SLU_{old} message, and now n_i receives SLU_{new}. If the SLU_{new} is received from the same node n_j with minimum TTL value, then its transmission stops at n_i, and thus, it is not forwarded. Contrarily, if a *node* n_i receives a SLU_{new} from a neighbor $n_k \neq n_j$, it will rebroadcast SLU_{new}, if and only if, n_i is MPR for n_k. Moreover, node n_i will also choose n_k as its next_hop relay towards sink. This local update mechanism in combination with efficient MPR broadcast will reduce the network energy consumption.

Moreover, we have introduced a preemptive buffering mechanism to minimize data loss between the mobile sink and its immediate neighbors. Indeed, data reports may suffer transmission losses between moving sink and its direct neighbors due to link breakages as sink may move away from relay nodes vicinity. In SN-MPR, sink transmits hello messages and SLU messages every two and five seconds respectively. Suppose at an instant t, a node n_i receives a *hello* message from the sink and a symmetric link is established between them. Afterwards, n_i will change this link to asymmetric if it does not receive any *hello* from the sink for 2 consecutive hello intervals, which could result in data loss. Suppose sink moves out of n_i's range at instant $t{+}\epsilon$. As n_i keeps on considering its link with the sink as symmetric for $t{+}4{-}\epsilon$ more seconds, all data transmitted to the sink during this duration is lost. To tackle this problem, sink's one-hop neighbors act as temporary roots if they do not receive sink's *hello* after *t+hello_interval*. As an act of precaution, sinks one-hop neighbors consider that sink may no longer be in their vicinity, and thus, they stop sending data reports to the sink. At the same time, they start buffering all incoming data packets and data reports generated by itself. These temporary data buffering roots will redirect the buffered packets to the sink when they receive updated sink location information either through a *hello* or *SLU* message.

The processing of a sink generated SLU message, reverse tree creation and local repair mechanism, when a node n_i receives SLU via an intermediate node n_j is explained in the pseudocode presented in the algorithm-7.

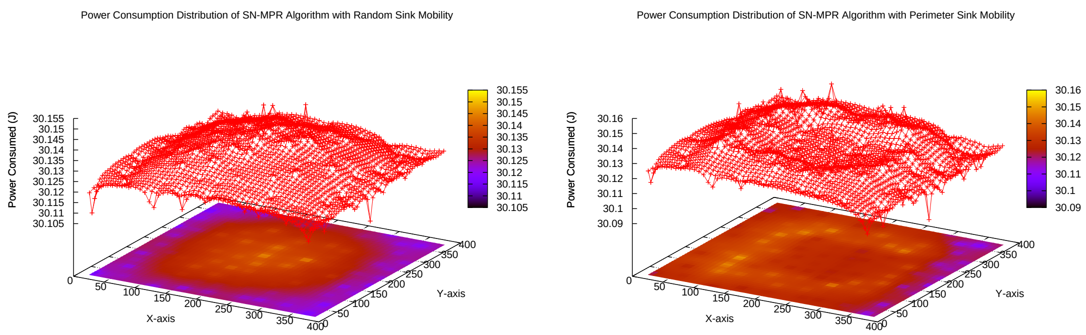
Algorithm 7 : SLU message processing and Tree formation algorithm at node n_i

```
Recv(SLU_new, n_j)
Initialize forward_SLU ← false

if !Symmetric_link(n_i, n_j)
        drop(SLU_new)
else
        // If the received SLU is seen for the first time, process it and update reverse tree route
        if (sequence_no(SLU_new) > sequence_no(SLU_last))
                if (is_MPR(n_i, n_j))
                        save(SLU_new)
                        delay_relay(SLU_new, delay_time)

                if (n_i→next_hop_sink==n_j)
                        distance_node_i,sink = ttl(SLU_new)
                        forward_SLU ← false;

                if (n_i→next_hop_sink != n_j)
                        n_i→next_hop_sink = n_j
                        distance_node_i,sink ← ttl(SLU_new)
                        forward_SLU ← true
        //if multiple copies of same SLU_new are received
        else if (sequence_no(SLU_new)==sequence_no(SLU_last))
                if (ttl(SLU_new)<=dist_i,sink))
                        next_hop_node_i,sink ← n_j
                        distance_node_i,sink ← ttl(SLU_new) n_j
                esle if (TTL(SLU_new) == dist_i,sink))
                        if (next_hop_i,sink == n_j)
                           forward_SLU ← false
        else
                discard(SLU_new)
// Once the approximated timer of receiving multiple SLU copies from different neighbors
   expires, retransmit the SLU_new stored in temporary buffer if n_i is MPR or n_j
Delay_relay(SLU_new, t)
        if (forward_SLU == true)
                decrement_ttl(SLU_new)
                broadcast(SLU_new)
```

3.1.5 Simulation and discussion

Extensive simulations were conducted to evaluate the performances of SN-MPR algorithm. The main performance metric of interest is the total energy consumption distribution under different sink mobility patterns. Indeed, a balanced distribution of the power consumption among nodes plays an important role in the lifetime of the network. We first considered a random mobility model of the sink and the total energy consumption distribution i.e. power consumed in transmission, reception and idle listening of the whole network is presented in the figure-3.2a. As can observed, SN-MPR algorithm balances the power consumption of the nodes in a very efficient way as the nodes end up consuming almost equivalent power of 30J each. However, nodes on the network perimeter consume lesser energy as they perform lesser relaying tasks. This effect is not due to the proposed algorithm but due to the random mobility model of the sink which causes the sink to move more around the central regions than at the network perimeter.

Next, the power distribution of the algorithm is evaluated using the perimeter mobility model in which the sink moves continuously at the network boundary. Such mobility is possible in some WSN deployments like in very harsh terrains where it may be physically impossible to enter the WSN deployment region or due to security reason as in battlefield environment. As depicted in figure-3.2b, the overall power consumption is uniform again throughout the network with most of the nodes consuming approximately 30J energy in their lifetime. However, as compared to the power distribution of the random sink mobility model, rather higher power consuming nodes are situated at the network boundaries in contrast to being at central region. This is due to the fact that when ever the sink is closer to a particular spot at the network perimeter, the MPRs around it have to relay the data traffic of all the network nodes behind it.



(a) With Random Sink Mobility

(b) With Perimeter Sink Mobility

Figure 3.2 – Total Energy Consumption Distribution of SN-MPR Algorithm

3.2 Duty-cycle routing in mobile sink WSNs

Publications : [15]
Transceiver is the major power consuming component of a wireless sensor device with nodes consuming power in transmission, reception, idle listening and sleep states. Among these four states, a transceiver wastes most of its energy in idle listening as WSN applications usually generate data at a low rate. Sensor nodes pass majority of their time in monitoring events, and only a fraction of time is spent in transmitting sporadic and/or periodic events to the sink. A node can minimize this power loss due to idle listening by switching its radio to sleep mode when it has no data to transmit/receive. This switching between active and sleep states is known as duty-cycling. However, duty-cycling requires a sleep scheduling mechanism whereby nodes select their active-sleep periods and coordinate with other nodes for exchanging traffic. This can be achieved either by exploiting topology control and/or power management schemes by controlling schedules at lower layers. The existing duty-cycling routing protocols can be broadly classified into Geographic routing and Topology Control routing. Duty-cycling geographic routing protocols are designed on the assumption that nodes know their location information, and they use it to route their traffic towards the sink node [12][66][33][48][55][35]. Nodes choose a next hop relay candidate to forward their information while the chosen next hop forwarder is not always in the active state due to asynchronous duty cycles. Contrarily, in duty-cycling topology control routing a small subset of network nodes needs to stay active to maintain the network connectivity, while the remaining redundant sensor nodes can switch to sleep state whenever they have no more data to transmit or receive. This exploitation of node redundancy to find the minimum subset of active nodes which form the connected network backbone is referred to as Topology Control. These data relaying active nodes can further minimize energy consumption by performing duty cycling i.e. such active nodes can switch off their respective transceivers when communication is not required and then switch between on and off states. However, such duty-cycling requires coordination among communicating neighbors as transceivers of both nodes should be active at the same time to exchange information. This scheduling of on/off states is mostly implemented as part of the MAC layer protocols [75][82][36][92][49]. In this work we address the energy minimization issue via topology control technique and present the duty-cycle aware SN-MPR algorithm at the network layer.

3.2.1 Duty Cycle SN-MPR Algorithm

We have proposed a distributive duty-cycle aware data dissemination algorithm for delay tolerant WSN applications in which sink is mobile and follows a sojourn based mobility model i.e. the sink anchors itself at its chosen sojourn points for certain duration in order to gather monitored information from the network and then moves on to another sojourn position. The proposed algorithm, named duty-cycle SN-MPR, is an adaptation of the previously proposed SN-MPR algorithm for duty-cycling environments. As in SN-MPR proposal, mobile sink in duty-cycle SNMR still uses *hello* messages for neighbor discovery and Multi-Point Relay (MPR) broadcast to disseminate its SLU messages to the network. Nodes use the reverse path of the forwarding tree of the SLU messages to disseminate their data reports to the sink. Duty-Cycle SN-MPR algorithm minimizes the power consumption of the network by allowing the leaf nodes (non-MPRs) in the data forwarding tree to switch-off their transceivers when they have no data to transmit, and then alternate between active and sleep states. Nodes switch to active state when sink arrives at a new sojourn position to receive sink location update message. When the sink's sojourn time $sojourn_t$ expires, all nodes switch-off their respective radios for $mobility_t$ seconds i.e. the time the sink will take to arrive at its destination. Since the transceivers are off during this period, all nodes buffer data reports generated by them and the packets to be relayed to the sink in their local memory. These buffered packets are delivered to the sink once it announces its new position via a SLU packet and the reverse routing tree rooted at the current sink sojourn position is re-configured. Finally, local path repair mechanism is no longer used in this new version of SN-MPR algorithm.

3.2.1.1 Sink Location Update messages

In addition to the information contained in the SLU messages of SN-MPR algorithm, the sink appends two additional parameters in those of duty-cycle SN-MPR. The first parameter is the sojourn duration $sojourn_t$. It is the time span the sink will remain stationary at the current sojourn position. This information enables the leaf nodes in the currently constructed reverse routing tree i.e. the non-MPRs, to switch-off their transceivers for $sojourn_t$ seconds. During this period, a leaf node only switches on its radio for few milliseconds when it has a data packet to transmit to its parent node. The second parameter is the mobility duration $mobility_t$. When the sink arrives at a sojourn position, it randomly selects its next sojourn position in advance and calculates the time duration it will require to move from the current position to the next one. It is supposed that the sink knows its mobility speed and, hence, can easily calculate its $mobility_t$ value using speed and distance between the current and next sojourn points.

The pseudocode of the SLU message processing and tree route formation at a node n_i when it receives an update from a neighbor node n_j is presented in the Algorithm-8.

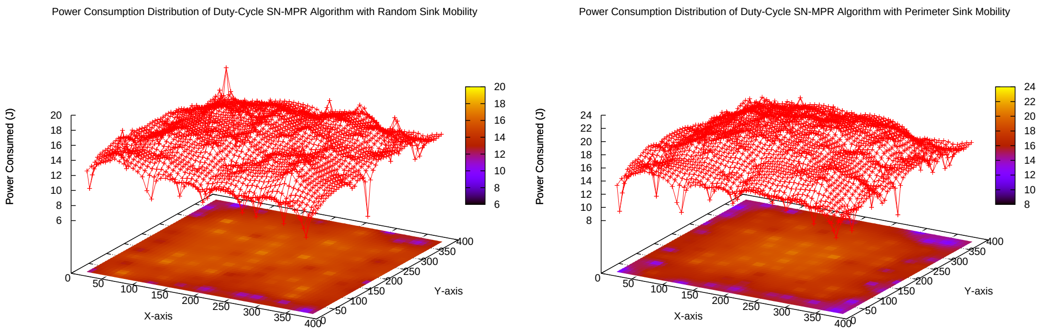
3.2.2 Simulation and discussion

As in SN-MPR, the main performance metric of interest in Duty-Cycle SN-MPR is the total energy consumption distribution and, hence, the network lifetime. We have evaluated the algorithm under random and perimeter sink mobility models. As shown in figure-3.3a, the duty-cycle SN-MPR algorithm offers very good power distribution under random sink mobility model and majority of the nodes consume power almost uniformly in the 16J to 18J range. These battery power consumption values are 33% to 50% lesser as compared to those of the previously proposed SN-MPR algorithm.

Algorithm 8 : SLU message processing and Tree formation algorithm at $node_i$

```
Recv(SLU_new, node_j)
Initialize sleep ← false
if !Symmetric_link(node_i, node_j)
        drop(SLU_new)
else
        // If this SLU is received for the first time process it
        if (sequence_no(SLU_new) > sequence_no(SLU_last))
                decrement_ttl(SLU_new)
                if (is_MPR(n_i, n_j))
                        sleep ← false
                        Broadcast(SLU_new)
                else
                        sleep ← true
                distance_{node_i,sink} = ttl(SLU_new)
                node_i→next_hop_sink = node_j
                sojourn_{i,t} = SLU_new→sojourn_t
                mobility_{i,t} = SLU_new→mobility_t
                //Leaf node switches off its radio till sink will arrive at its next sojourn position.
                  During the 1st sojourn_{i,t} seconds, n_i alters between active/sleep states for
                  sending data reports. After that all nodes switch off their radios during sink
                  mobility.
                Duty-cycle(sojourn_{i,t} + mobility_{i,t})

        //multiple copies received
        else if (sequence_no(SLU_new)==sequence_no(SLU_last))
                if (ttl(SLU_new)<=dist_{i,sink}))
                        next_hop_{node_i,sink} ← node_j
                        distance_{node_i,sink} ← ttl(SLU_new)

        //old SLU received
        else
                discard(SLU_new)


Duty-cycle(sojourn_t, mobility_t)
if (sleep is true) // Non-MPR node
        radio_sleep(now, sojourn_t+mobility_t)
else // MPR node
        radio_sleep(now+sojourn_t, mobility_t)
```

The power distribution when the sink follows the perimeter mobility model and thus moves at the border of the network is presented in the figure-3.3b. As can be observed, the overall energy consumption distribution is again pretty uniform, but like a similar observation with the SN-MPR algorithm, nodes consume more average power than the random sink mobility model, both in the central region and on the perimeter.



(a) With Random Sink Mobility

(b) With Perimeter Sink Mobility

Figure 3.3 – Power Consumption Distribution of Duty-Cycle SN-MPR

Chapter 4

VEHICULAR AD HOC NETWORKS

In this chapter, we present our contributions in connected and autonomous vehicles which mainly deal with multi-hop routing. We first present a Geocast routing scheme we have proposed for vehicular ad hoc networks (VANETs) with the aim of decreasing data overhead in the network and hence saving bandwidth. We then present a routing protocol we have proposed for unmanned aerial vehicles (UAVs) based on some swarm intelligence algorithms for the purpose of connectivity maintenance of active paths. These contributions are done within the PhD thesis of *Salim Allal* and *Nour E. Bahloul*.

4.1 Geocast routing in VANETs

Publications : [2][17][41][42]
Routing in VANETs is very challenging due to the high speed of vehicles making topology of the network highly dynamic and causing frequent links disconnections. As shown in figure 4.1, literature provide us with a large range of routing solutions for VANETs which can be classified into different categories according to their routing principles.

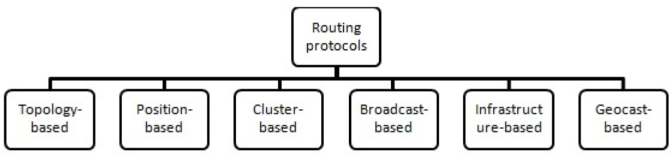


Figure 4.1 – Categories of routing protocols in VANETs

Among these categories, geocast routing seems to be the most appropriate routing family for VANETs according to some comparison studies [87][40][51][41]. Geocast routing follows the principle of routing data packets from a single source vehicle to all vehicles belonging to the destination area called zone of relevance ZOR. Literature provides a large range of papers dealing with geocast routing in VANETs [10][61][15][30][59][7][17][31][84][60]. These protocols differ from each other according to the used relay selection technique (beacon-based or beaconless-based), the used recovery mode strategy or the used forwarding strategy. Most of them, however, share the assumption that the form of ZORs is of circular or rectangular shape and confined in a unique geographical zone. This makes the representation of forms of ZORs, their origin and positioning arbitrary and chosen according to the scenarios and needs of the authors.

In this work, we introduced a new geocast routing protocol for VANETs named GeoSUZ. The corner stone of this protocol is an optimal flooding mechanism based on a geometrical vision angle technique to transmit messages from a single source to all vehicles located in a ZOR. For that purpose, forwarding areas called zones of forwarding, ZOFs, were introduced to confine the message forwarding until it reaches the ZOR. For an easy mathematical representation of ZOFs, simple geometrical forms were used.

4.1.1 GeoSUZ Protocol

GeoSUZ algorithm can be implemented on the on-board units of vehicles for the purpose of road accidents management. It will consider the position of the concerned vehicle, the traffic rules and a digital map of the city in order to process designations of relevant destination zones called sub-ZORs. However, we delegate the affectation of these sub-ZORs to a competent authority such as road safety services, which will provide the coordinates or designations of stretches of roads where vehicles will be likely affected by an event. As illustrated by figure 4.2, if the red star represents an accident that happens in lane B_l (the left lane of the road B after the junction), vehicles belonging to sections $A_l(Z_1)$, $A_r(Z_3)$ and $B_l(Z_2)$ at the entrance of the junction need to be informed about the accident making them taking the decision to bypass the accident point.

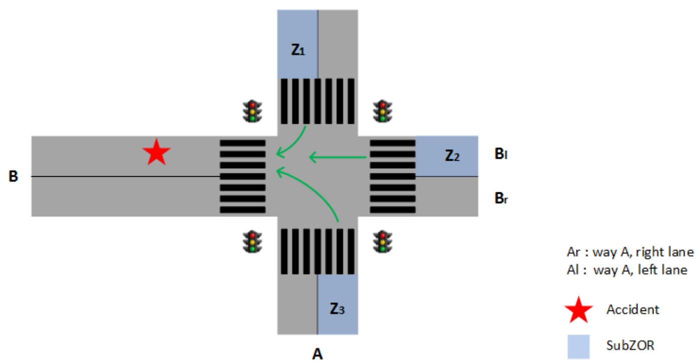


Figure 4.2 – Example of relevant Sub-ZORs

4.1.1.1 Zone of Relevance shapes

In order to cover all forms of roads, we consider that road network is represented by a two dimensional euclidean plane geometry. Thus, we have chosen to consider three simple geometrical forms of *ZOR*s: the circle shape represented by the coordinates of its center c and those of one point of its contour d $\{(x_c, y_c), (x_d, y_d)\}$, the triangle T represented by the coordinates of its three corners$\{a(x_a, y_a), b(x_b, y_b), c(x_c, y_c)\}$, and the quadrilateral Q represented by the coordinates of its four corners $\{a(x_a, y_a), b(x_b, y_b), c(x_c, y_c), d(x_d, y_d)\}$. The three considered shapes are enough to cover curved routes as illustrated in figure 4.3.

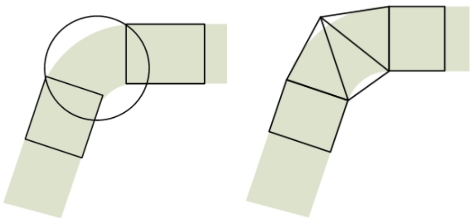
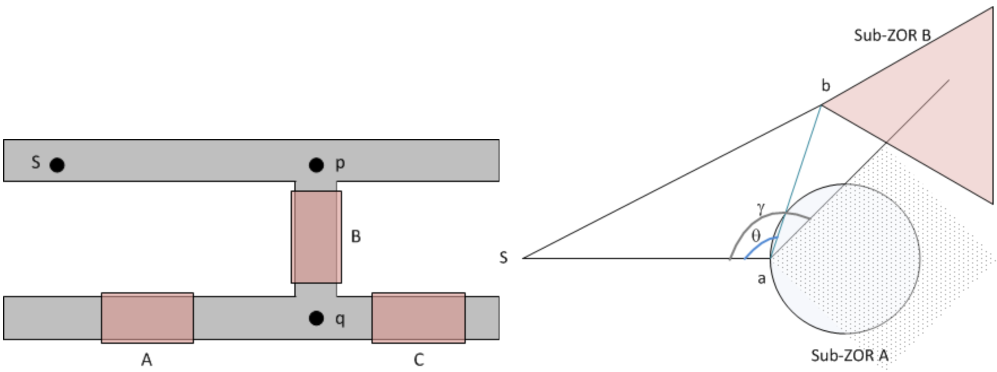


Figure 4.3 – Curved routes covered by the 3 shapes

4.1.1.2 Vision angle forwarding technique

We consider the scenario of road network illustrated in figure 4.4a, where S represents a unique source vehicle and A, B, and C the sub-*ZOR*s composing the same *ZOR*. Thus, the same message will take approximately the same path to reach A, B and C through vehicles p and q. The use of greedy forwarding will generate 3 times the same stream (destined to A, B and C) at p-level and 2 times the same stream (to A and C) at q-level.



(a) Road network scenario (b) Vision angle technique

Figure 4.4 – Geometrical vision angle based routing technique

Before a source S sends a geocast message, it calculates the distance between its own position and the nearest point of the destination ZOR (or the different sub-

ZORs). Depending on the form of the destination sub-ZOR, this distance is equal to $\min(d_{Sd}, d_{Sc}) = d_{Sd}$ in the case of a circle, $\min(d_{Sa}, d_{Sb}, d_{Sc})$ in the case of a triangle, and $\min(d_{Sa}, d_{Sb}, d_{Sc}, d_{Sd})$ in the case of a quadrilateral. Once the distances are computed, they are then used in our vision angle technique as illustrated in figure 4.4b where we consider S as the source of the geocast message M, and A and B two sub-ZORs constituting the total ZOR. Thus, when S needs to inform the sub-ZORs A and B about an event, it firstly calculates the distances d_{Sa} and d_{Sb}. In our case, sub-ZOR A is closer to S than sub-ZOR B ($d_{Sa} < d_{Sb}$). Then, S needs to know if sub-ZOR B is accessible via sub-ZOR A or, does B belongs to the vision angle of S through A. The angle θ represents the angle $\hat{Sab}$ of the triangle Sab. The angle γ, is an arbitrary vision angle fixed according to different parameters (speed of vehicles, number of vehicles, etc.). Applying the condition 4.1 to the scenario above, we conclude that sub-ZOR B is not in the same direction as sub-ZOR A. So, source S sends two occurrences of the same geocast message M destined to A and B respectively.

$$(cos(\theta) = \frac{Sa^2 + ab^2 - Sb^2}{2 * Sa * ab}) \geq cos(\gamma) \tag{4.1}$$

If $\theta \leq 90°$, the source S sends two messages to the sub-ZORs A and B. If $\theta \in]90°, 180°]$, S sends one message intended to reach A and B (via A).

As a reminder, the distance between two points $A(x_A, y_A)$ and $B(x_B, y_B)$ in a two-dimentional plan is defined as in equation 4.2.

$$d_{AB} = \sqrt{(x_B - x_A)^2 + (y_B - y_A)^2} \tag{4.2}$$

4.1.1.3 GeoSUZ Algorithms

We describe a ZOR as a set of sub-ZORs, $subZOR_1 \cup subZOR_2 \cup ... \cup subZOR_n$, where $n \geq 1$. We also define the geocast message M as $M[m, S, Z]$, where $M[m]$ is the message content, $M[S]$ is the sender ID, and $M[Z]$ the coordinates of the destination ZOR area. When the same geocast message destined to two sub-ZORs Z_1 and Z_2 (or more) follows the same path due to the use of a recovery mode in greedy forwarding technique, the message M is pre-fragmented and defined as $M_1[m, S, \{Z_1\}].M_2[m, S, \{Z_2\}]$. In Algorithm 9, $RM(Z_1)$ refers to the recovery mode procedure applied to the sub-ZOR Z_1, and $GF(Z_2)$ the greedy forwarding procedure applied to the sub-ZOR Z_2. Thus, we can read the first test as: if there is no neighbor using greedy forwarding method to reach the first sub-ZOR Z_1 while there is a neighbor to reach Z_2, and the recovery mode of Z_1 gives us the same neighbor to reach Z_2 using greedy forwarding, then we pre-fragment the message M and send it to that neighbor.

Algorithm 9 : Pre_fragment($M[m, S, \{Z_1, Z_2\}]$)

IF [not($GF(Z_1)$) and $GF(Z_2)$ and $RM(Z_1)$==$GF(Z_2)$] or [$GF(Z_1)$ and not($GF(Z_2)$) and $GF(Z_1)$==$RM(Z_2)$] or [not($GF(Z_1)$) and not($GF(Z_2)$) and $RM(Z_1)$==$RM(Z_2)$] THEN return ($M_1[m, S, \{Z_1\}].M_2[m, S, \{Z_2\}]$) ; ENDIF

As illustrated in Algorithm 10, when the current node is able to perform the greedy forwarding, it fragments the message into different sub-messages addressing the different sub-ZORs. The pre-fragmented message becomes $M_1[m, S, \{Z_1\}], M_2[m, S, \{Z_2\}]$. Here, we note that the two messages $M_1$and M_2 are forwarded separately in different paths.

Algorithm 10 : Fragment($M_1[m, S, \{Z_1\}].M_2[m, S, \{Z_2\}]$)

IF [$GF(Z_1)$ and $GF(Z_2)$ and $GF(Z_1)$=!$GF(Z_2)$] or [not($GF(Z_1)$) and $GF(Z_2)$ and $RM(Z_1)$=!$GF(Z_2)$] or [$GF(Z_1)$ and not($GF(Z_2)$) and $GF(Z_1)$==$RM(Z_2)$] or [not($GF(Z_1)$) and not($GF(Z_2)$) and $RM(Z_1)$==$RM(Z_2)$] THEN return ($M_1[m, S, \{Z_1\}], M_2[m, S, \{Z_2\}]$);

The pre-fragmented messages can be defragmented in case the sub-ZORs are currently able to be addressed sequentially (Algorithm 11). Thus, a pre-fragmented message becomes $M[m, S, \{Z_1, Z_2\}]$. Notice that a fragmented message cannot be defragmented.

Algorithm 11 : Defragment($M_1[m, S, \{Z_1\}].M_2[m, S, \{Z_2\}]$)

IF [$GF(Z_1)$ and $GF(Z_2)$ and $GF(Z_1)$==$GF(Z_2)$] THEN return($M[m, S, \{Z_1, Z_2\}]$);

We present the full steps of our GeoSUZ routing protocol in Algorithm 12. The source vehicle (or intermediate relay vehicles) defines its γ angle then calculates and orders all distances between itself and the different sub-ZORs. At this time, it generates the geocast message M intended to reach all the sub-ZORs. Here, the test if the current node belongs to the nearest sub-ZOR is done. If it is true, then it broadcasts (only in the current sub-ZOR) the message M, removes the current sub-ZOR from M and tries out the pre-fragment procedure which processes the geomertical vision angle technique as depicted in Algorithm 13. After that, a set of tests on the message M are made. When M is pre-fragmented, it is geoUnicasted. When it is fragmented, two messages M_1 and M_2 are GeoUnicasted. Now, if it is neither one nor the other case, the message is defragmented and GeoUnicasted to the last or the unique sub-ZOR.

4.1.2 Simulation and discussion

In our simulation, we have compared the performances of our geocast routing protocol to those of the Greedy Perimeter Stateless Routing protocol (GPSR) [8], which is a well known routing protocol for wireless networks based on greedy forwarding technique. The obtained results from the application of the two protocols to several road scenarios,

Algorithm 12 : GeoSUZ algorithm

Define γ
Calculate all $D_{SZ_i}$where Z_i the sub-ZOR $i : i = 1, 2, ..., n$
Ascending order of D_{SZ_i}into D_{SZ_k} where $k = 1, 2, ..., n$
GENERATE($M[m, S, Z_k]$); // S generates or receives M
IF Current_Node in $M[Z[1]]$ THEN
GeoBroadcast($M[m, S, Z[1]]$);
SUB($Z[1]$, M); // $M[m, S, Z \setminus Current\_subZOR]$
PREFRAGMENT(M); //$M_1[m, S, Z].M_2[m, S, Z]$ in Algorithm 13
END IF
\\ Pre-fragmentation
IF (pre_fragment(M)) THEN
GeoUnicast(M);
ELSE \\ Fragmentation
IF (fragment(M)) THEN
GeoUnicast(M_1);
GeoUnicast(M_2);
ELSE \\ Defragmentation
IF (defragment(M)) THEN
GeoUnicast(M, GF($M_1[Z[1]]$));
END IF
END IF
END IF

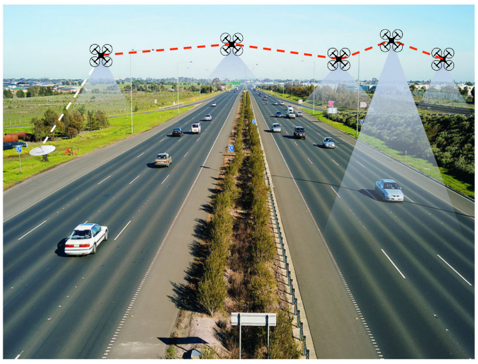
Algorithm 13 : PREFRAGMENT vision angle based procedure

$h = 1$; // Z_h the nearest sub-ZOR
$M_1[Z] = Z_h$;
$M_2[Z] = \phi$;
$j = 1$;
WHILE $j < k$ THEN
IF $S\hat{Z_h}Z_{j+1} \geq \gamma$ THEN
ADD(Z_{j+1}, M_1); // $M_1[m, S, \{Z_h, Z_{j+1}\}]$
ELSE // $S\hat{Z_h}Z_{j+1} < \gamma$
ADD(Z_{j+1}, M_2);
END IF
$j = j + 1$;
END WHILE

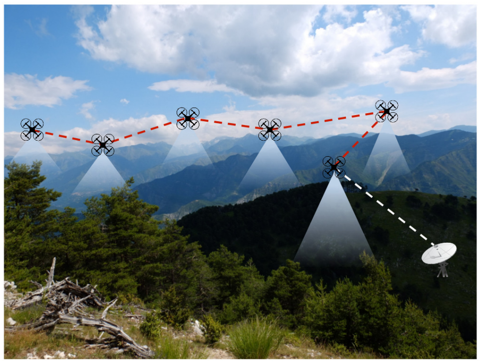
shows that GeoSUZ algorithm outperforms GPSR and allows a considerable gain of bandwidth by significantly decreasing the number of messages sent over the network.

4.2 Routing in UAVs

Publications : [10][25][28]
An ad hoc network of cooperative drones may be of interest for cost reasons, but also in places where there is no cellular coverage due to the complexity to reach these places and install fixed relays, or due to the damage of existing infrastructure after a natural disaster. Figure 4.5a shows a fleet of UAVs cooperating in an ad hoc manner to monitor a highway and transmit traffic information to ground stations. This application has recently been adopted by the french highways operator VINCI [1]. The main encountered issue, however, is the limited radio range of the drones for a real-time transmission when the drones are far away from ground base stations and flying in areas where cellular coverage is missing. Another application is shown in figure 4.5b where a fleet of drones cooperate to relay information of each other to monitor wild environments and detect the start of fire. Indeed, thousands of hectares burn down every year in south of France and in other mediterranean countries due to late detection of a fire especially in hard-to-reach areas [79] [2]. The civil security direction in France has been working for a few years on how to use UAVs to identify the counters of a disaster in real time [3].



(a) Highway surveillance



(b) Forest fire surveillance

Figure 4.5 – Surveillance scenarios with collaborative UAVs

This kind of collaborative networks, however, may be faced to many challenges, mainly the high mobility of the drones and connectivity maintaining. Indeed, the high mobility of the drones may cause frequent and rapid changes in network topology and hence links failure. Moreover, each drone has the possibility to move according to an independent preprogrammed flight plan and the network can often get partitioned. Several routing solutions for UAVs have been proposed in literature [21][77][63][26][4][53][50].

[1] http://www.lefigaro.fr/societes/2015/08/01/20005-20150801ARTFIG00050-des-drones-pour-surveiller-le-trafic-sur-les-autoroutes.php

[2] http://www.statistiques.developpement-durable.gouv.fr/lessentiel/ar/368/1239/feuxforet.html

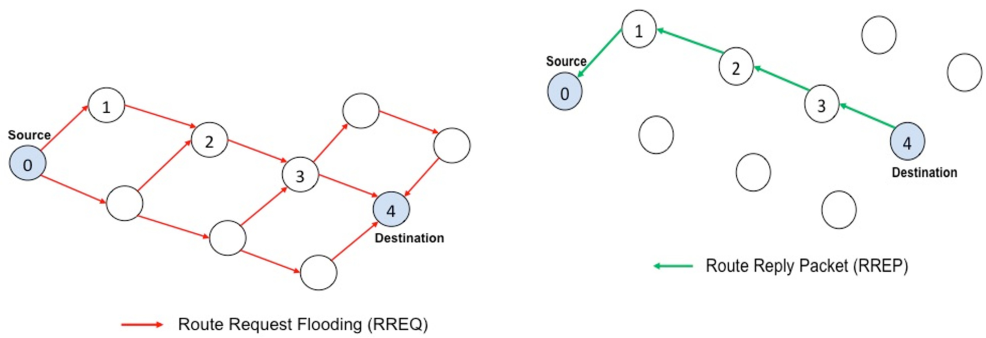
[3] http://www.interieur.gouv.fr/Actualites/Dossiers/Les-drones-au-servicede-la-securite/Identifier-en-temps-reel-les-contours-d-un-sinistre

However, almost all of them are either suitable for delay tolerant applications or only limited to assure the connexion between distant ground groups throw relay drones.

To cope with real-time aspect, we have proposed a strategy to compute a transmission path and maintain its connectivity in a collaborative UAV network while transmitting data, or while the computed path is still active. The proposed mechanism is called BR-AODV and combines the advantages of the on-demand routing protocol AODV [69], suitable for ad hoc networks with high mobility, and the Boids of Reynolds mechanism [74] to control the mobility of the drones involved in a transmission path.

4.2.1 BR-AODV Protocol

Many studies have shown that AODV routing protocol seems more appropriate for networks with low density [9], which is the case of the considered drone network. Moreover, proactive routing schemes in a highly dynamic context such as UAV networks is not suitable. Indeed, entries in the routing table become rapidly no longer valid due to the velocity of the drones and frequent topology changes. As a result, the protocol BR-AODV uses almost the same basic elements of AODV, with the same exchanged types of packets, and the same structure of routing tables. A source node diffuses a RREQ message to its direct neighbors and the recipients set up backward pointers to the source and forward the RREQ message if the route to destination is not found locally (figure 4.6a). When the destination node (or any other intermediate node who knows the route to destination) is reached, it proceeds with a unicast transmission of the RREP message along the shortest path to the source node (figure 4.6b).



(a) Broadcast of the RREQ packet (b) Unicast transmission of the RREP packet

Figure 4.6 – On demand route discovery mechanism

However, as we can see in the two following sections, route discovery and route maintenance mechanisms of AODV have been changed in the proposed BR-AODV protocol.

4.2.1.1 Route discovery

In BR-AODV, the destination address of RREQ messages is set to broadcast address and is diffused to the direct neighbors of the source node. The recipients forward the RREQ message only if they do not have a direct link to a ground base station. Nodes with direct links to ground base stations stop forwarding and proceed with a unicast transmission of the RREP message along the shortest path to source node. The source node chooses the closest ground base station among all the received RREP messages.

Links with ground base stations are maintained in a proactive manner throw drone and network association (DNA) messages issued periodically by ground base stations. The DNA messages contain sufficient information for the recipients to construct an appropriate routing entry to the closest base stations. They are sent as the data part of IP packets with the TTL field set to 1 to limit their diffusion to the 1-hop neighborhood of the ground base stations. The DNA message is inspired from HNA (Host and Network Association) message of OLSR protocol [19] except that the DNA message is not relayed.

4.2.1.2 Route maintainance

To cope with dynamic topology changing in an UAVs network and for the purpose of connectivity maintaining of active paths as long as they are needed by the emitting sources, the AODV routes maintaining process has been replaced in BR-AODV with a mobility control module performed by applying the principle of maintaining training in Boids of Reynolds to the movement of UAVs. Indeed, Craig Reynolds has introduced three basic rules that achieved the first simulated flocking in computer animations [74]. He achieves a graphical application where agents he calls boids move coherently in a virtual environment and models an emergent behavior where each boid acts autonomously while respecting three simple rules; the separation rule where the boid moves away when it is too close to another boid, the cohesion rule where the boid tries to get closer to its nearest neighbors when it is too far from the group, and the alignment rule where the boid continually seeks to adjust its speed to the average speed of its neighbors and to remain in the common direction of displacement. The BR-AODV mobility control module is a combination of these three rules where each UAV participating to active paths, plans its displacement when moving to avoid any disconnection in these paths.

We consider a network of autonomous UAVs where each UAV i has a velocity v_i and a two-dimentional position $p_i(x_i,y_i)$ which is referred to as p_i. The principle of Boids of Reynolds is applied to control the movement of the nodes that participate in one or more active paths. Thus, each node which contributes to routing data in these paths is handled as a boid in a swarm comprised of all active nodes belonging to active paths. In simulation terms, the problem formalization is made by a group of boids $B = b_1,b_2, \ldots ,b_n$ which represents all the UAVs constituting the active paths, where each is placed in a position p_i. The variable δ_i is defined as the group of boids situated inside the radio range of radius z of boid b_i. Each boid b_i moves with a velocity v_i according to the three previous rules which are expressed by the formulas below. The calculation should take into account each of its boid neighbors (in radio range z) b_j in group δ_i, with their parameters, i.e., the position p_j and the velocity v_j. The vectors defined by the positions of the boid b_i and each of its visible boids b_j are summed and the separation velocity denoted by v_{s_i} is calculated as the negative sum of these vectors :

$$v_{s_i} = - \sum_{b_j \in \delta_i : d(b_j, b_i) < z} (p_i - p_j) \tag{4.3}$$

The alignment velocity denoted by v_{a_i} is calculated as the average speed of the visible neighbors of b_i. The boid b_i slows or accelerates according to its neighbors b_j. If a boid accelerates too much, it may go out of the visibility fields of the other boids and out of the group eventually. If there is no boid directly visible, v_{a_i} is equal to zero :

$$v_{a_i} = \frac{1}{|\delta_i|} \sum_{b_j \in \delta_i} v_j \tag{4.4}$$

The cohesion velocity of the boid b_i is denoted by v_{c_i}. It acts as a complement to the separation and is calculated in two steps. First, the center of the set δ_i of the directly visible boids b_j is computed. This center is denoted by c_i and corresponds to the density center of all visible boids. Then v_{c_i} is calculated as follows:

$$v_{c_i} = c_i - p_i \ Where \ c_i = \frac{1}{|\delta_i|} \sum_{b_j \in \delta_i} p_j \tag{4.5}$$

Now we can compute the movement speed of each boid i at time *t+1* as follows:

$$v_i(t+1) = \alpha(w_s v_{s_i}(t) + w_a v_{a_i}(t) + w_c v_{c_i}(t)) + (1-\alpha) v_i(t-1) \tag{4.6}$$

Where the smoothing parameter α in [0-1] interval indicates how much previous information gathered by a node is incorporated into its new deployment decision. Indeed, the current velocity of a node may include important information about the previous interactions of the node. Hence, α can be considered as a memory parameter.

The parameters v_{s_i}, v_{a_i} and v_{c_i} are the velocities of node i due to separation, alignment and cohesion behaviors respectively, and w_s, w_a and w_c are their corresponding weights taken in [0-1] interval. As shown in figure 4.7, the resulting velocity of each node i along our active path is a combination of its current velocity and the new information gained by its separation, alignment, and cohesion behaviors. These coefficients indicate the influence rate of each force and current perception of an UAV on its decision to move. By setting weights w_s, w_a and w_c, various node behaviors can be modeled.

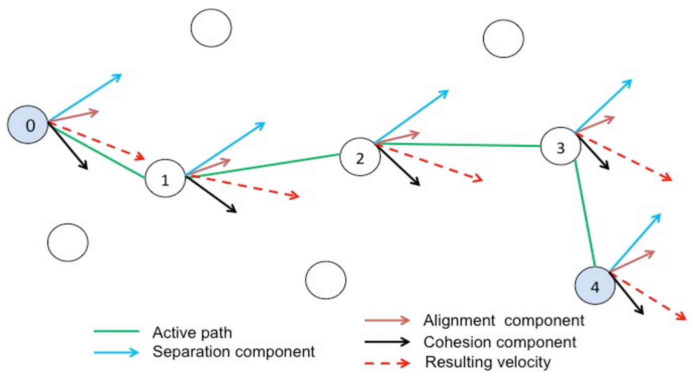


Figure 4.7 – Mobility control mechanism of BR-AODV

The new position p_i of the UAV at time *t+1* is calculated from its previous position at time t and its velocity v_i at time *t+1*. The resulting motion is expressed as :

$$p_i(t+1) = p_i(t) + v_i(t+1) \tag{4.7}$$

The calculation and the displacements above concern each node belonging to one or more active paths; they are summarized in Algorithm 14 where we can see the velocity vector affectation for each node i, after respectively computing the separation, the alignment, and the cohesion velocities with each neighbor j. The displacements of the nodes that do not participate in routing of active paths are not concerned by these rules; they rather obey to the strategy adopted by the task to achieve.

4.2.2 Simulation and discussion

As mentioned in the related work, UAVs nodes in most of the proposed routing protocols for UAVs in the literature are mainly limited to play the role of relays for disjoint mobile ad hoc groups on the ground. Hence, we thought more appropriate to compare the performance of BR-AODV with that of AODV rather than those of any other routing proposals for UAVs. The testing scenario consists in several UAVs deployed and moving independently while they organize them-selves as a flock, or swarm, to maintain the connectivity of an active transmission path, and make the implicated relaying nodes move as a flock along with the transmitter. In this purpose, we simulate a traffic flow transmission between 2 UAVs in the UAV fleet separated by 4 hops or 3 relaying nodes. Each node is equipped with the IEEE 802.11g radio interface and as boids parameters, we fixed the separation distance to 200 meters, the alignment distance to 220 meters and the cohesion distance to 250 meters with a maximum UAV speed set to 10m/s. These parameters values are set according to the maximum range of the UAVs

Algorithm 14 : connectivity maintaining at node$_i$

for each *node* ***in*** *nodes* ***do***
  begin separation: $v_{node}^{Sep} = 0,\ neighbors = 0$
    for each *other_node* ***in*** *nodes* ***do***
      if $(dist(node, other\_node) \leq \gamma_{sep})$
        $v_{node}^{Sep} \leftarrow v_{node}^{Sep} - (node.position - other\_node.position)$
        $neighbors++$
      end if
    end for
    $v_{node}^{Sep} \leftarrow \frac{v_{node}^{Sep}}{neighbors}$
  end separation
  begin alignment: $v_{node}^{align} = 0,\ neighbors = 0$
    for each *other_node* ***in*** *nodes* ***do***
      if $(dist(node, other\_node) \leq \gamma_{align})$
        $v_{node}^{align} \leftarrow v_{node}^{align} + (other\_node.velocity - node.velocity)$
        $neighbors++$
      end if
    end for
    $v_{node}^{align} \leftarrow \frac{v_{node}^{align}}{neighbors}$
  end alignment
  begin cohesion: $v_{node}^{coh} = 0,\ neighbors = 0$
    for each *other_node* ***in*** *nodes* ***do***
      if $(dist(node, other\_node) \leq \gamma_{coh})$
        $v_{node}^{coh} \leftarrow node.c + node.position$
        $neighbors++$
      end if
    end for
    $node.c \leftarrow \frac{node.c}{neighbors}$
    $v_{node}^{coh} \leftarrow node.c + node.position$
  end cohesion
  $node\_velocity \leftarrow (1-\alpha)node\_velocity + \alpha(w_s v_{node}^{Sep} + w_a v_{node}^{align} + w_c v_{node}^{coh})$
  $node_{position} \leftarrow node_{position} + node_{velocity}$
end for

radio transmitter, the IEEE 802.11g radio range values and the UAVs most frequently encountered velocities. We then set the weight parameters ws, wa and wc to 1 to make the separation, alignment and cohesion velocities equally important. Finally, we set the smoothing or memory parameter to 0.5 to moderately consider the importance of the previous velocity of a node in the computation of its current velocity.

We defined a best effort transfer between the source and the destination and we measured its throughput, its packet drop rate and its end-to-end delay for various background traffic load. In this purpose, we added 10 nodes that generate this background traffic load, at a constant bit rate, in addition to 5 ground base stations which periodically broadcast DNA messages every 5 seconds in their vicinity. The obtained results show that BR-AODV outperforms AODV for all these metrics thanks to its ability to maintain active paths connectivity and to avoid re-routing mechanisms.

Chapter 5

Conclusion and Perspectives

This chapter presents the general conclusions of this manuscript and then lists a number of future research directions.

5.1 Conclusions

In this manuscript, I highlighted my main research activity during the last ten years. This research activity mainly focuses on the design of distributed systems in wireless ad hoc networks, with special interest to data dissemination protocols and architecture design in wireless eHealth systems (WBANs), large scale wireless sensor networks (WSNs), and vehicular ad hoc networks (VANETs/UAVs). The manuscript is structured in three main chapters (2, 3, 4) corresponding to my main contributions around the three previously mentioned applications of wireless ad hoc networks.

Chapter 2 deals with wireless body area networks (WBANs). I first presented a deep analysis on the energy consumption of one-hop vs multi-hop communications in WBANs. In fact, some recent literature on WBANs presents deliberate use of multi-hops to transfer data from a sensor to the gateway via relay health sensors as more energy efficient than single hop communication. Other studies, however, argue contrarily. To this end, we have analyzed the single vs multi-hop energy consumption effect for real very short range sensor devices. The obtained results show that deliberate reduction of transmission range to induce multi-hop scenario in a WBAN is not energy efficient. Considering this conclusion and with respect to the recommandation emitted in the IEEE 802.15.6 standard for wireless personal networks, we have proposed several scenario driven 2-hop routing algorithms for intra-WBAN data dissemination.

Second, I presented our work on the communication between the WBANs themselves to enhance the transmission quality and optimize energy consumption by defining cooperative mechanisms. In fact, from the observation that for many other application areas WBAN subjects are in group, the inter WBAN cooperation is necessary. We thus defined a concept of network of BANs, named NetBAN, where subjects can share information and help each other in relaying data and optimizing energy consumption. A routing protocol intending to enhance energy and prolong network lifetime has been defined, implemented and evaluated. The obtained results show that this inter-WBANs relaying mechanisms are very helpful in optimizing energy consumption, increasing data delivery, and increasing network lifetime if they are used when necessary.

Third, given that within a WBAN it was demonstrated that a two-hop topology is more efficient than one-hop for interferences mitigation and that nodes can be located far from the coordinator needing a relay node, we found interesting to define cooperation mechanisms at MAC level. We thus defined a MAC cooperative mechanism that decodes and merges data at a relay node what increased the data delivery and the ability to transmit even in interference conditions without increasing energy consumption.

Our fourth contribution in WBANs deals with Quality of Service (QoS). We have proposed a scheduling strategy at the coordinator of a WBAN called PWRR (Priority-Weighted Round Robin) to bridge sensitive data from WBAN to peer-networks. The proposed scheduling strategy provides good results in terms of reducing delay of emergency and medical data. Indeed, simulation and analytical results for peer-networks involved in a WBAN based health monitoring system show that, if PWRR is set, the behavior of WIFI, WIMAX and LTE networks remains the same in keeping all flows as per their priorities by mitigating the end-to-end delay.

Chapter 3 deals with routing in large scale wireless sensor networks (WSNs). We have proposed two distributed energy-efficient sink location update algorithms for large scale wireless sensor networks in which the sink is mobile. First algorithm, named SN-MPR, uses a combination of multi-point relay broadcast and local path repair mechanism by means of which sink's location update packets are forwarded only to nodes which are affected by sink mobility; the rest of the network does not receive these update messages. At the same time, sink ensures continuous connectivity with sensor nodes. It is designed for applications which have rather stringent data delivery requirements.

The second algorithm, a modified version of SN-MPR named duty-cycle SNMPR, further minimizes the power consumption of the network by enabling the non-relay nodes to switch-off their respective transceivers when they don't want to communicate.

The simulation results show that both of these algorithms significantly reduce the power consumption of the network without compromising data delivery efficiency when compared to classical MPR flooding. Moreover, the mobility of the sink makes the overall energy consumption distribution among nodes in the network pretty uniform.

Chapter 4 deals with connected and autonomous vehicles. First, I introduced our proposed Geocast routing protocol, named GeoSUZ, for vehicular ad hoc networks (VANETs). The proposed protocol is based on a geometrical vision angle technique which allows to know if two zones of relevance, named ZORs, are in the same direction in order to send them a single message and hence, reduce messages overhead. For that purpose, we choose simple geometrical forms of ZORs so that they would be easy to implement and represent mathematically. Compared to a well known Geocast routing protocol GPSR [8], simulation results show that GeoSUZ algorithm significantly reduces the number of messages sent over the network and hence, saves bandwidth.

Second, I introduced our proposed routing protocol for unmanned aerial vehicles (UAVs) called BR-AODV. The protocol is based on AODV, a well known routing protocol for ad hoc networks suitable for UAV networks for on-demand route computation, and the Boids of Reynolds mechanism which is a kind of swarm intelligence for active paths connectivity maintenance while data is being transmitted. Moreover, an automatic ground base stations discovery mechanism was introduced for an association of proactive drones and ground networks. This mechanism is necessary in the context of real-time applications. The performance of BR-AODV was evaluated and compared with that of classical functioning of AODV. The obtained results showed that BR-AODV outperforms AODV in terms of end-to-end delay, throughput and packet loss rate.

These contributions constitute the core of my research activity and were addressed within four fully supervised PhD thesis. There are a number of other research achievements done within some other co-supervised PhD thesis, I briefly present some of them in Annex A. All these contributions have been peer-reviewed and published in international journals and conferences as listed in Annex B.

5.2 Perspectives

I have identified a number of research directions to explore in the short to mid term future and some of them are already ongoing. They range from the requirements of WBANs within the context of smart cities, to end-to-end quality of service (QoS) in heterogeneous networks of connected and autonomous vehicles.

Quality of service in 5G based HMS.
We are currently addressing the end-to-end quality of service (QoS) issue in a health monitoring system (HMS) within a 5G peer network. For this end, we are considering connected health sensors as well as the remote 5G cellular radio network. We aim to combine our previously proposed scheduling strategy at the coordinator PWRR (Section 2.4.2), with new service differenciation strategies for a reliable transmission of priority packets on the 5G radio interface. In this purpose and to mitigate the end-to-end delay of emergency and medical data flows, we are working on the improvement of the regular ACB (Access Class Baring) method at the 5G side with respect to the previously defined medical traffic categories and to their access delay budget and drop rate.

HMS requirements in the context of smart cities.
To extend our proposed inter-WBANs data transmission scheme in case of coordinators' energy issue (Section 2.2), we aim to involve other connected entities in the transmission process within the context of smart and connected city. Indeed, some trusted vehicles such as public buses, ambulances, police vehicles and so on, if equipped with wireless devices are all significant elements that can improve the connectivity of a WBAN network and thus participate to the transmission process of emergency and medical data flows. Patients equipped with physiological connected wireless sensors could dump, during each contact, all the medical information collected so far, or pieces of information mainly in the case where contact times are short and not sufficient to transfer all of the information collected from a patient's medical sensors. These informations could then be transmitted via multi-hop schemes till it reach hospital central servers for instance. This can improve the immediate availability of paths for emergency data transmission. However, this will raise a number of issues to resolve along the communication chain. We mainly aim to address the end-to-end quality of service (QoS) in terms of delay, through the mapping of service classes of the multiple involved heterogeneous networks. We also aim to explore vehicles' mobility plans when known, as it is the case for the buses, for the design of deterministic and efficient routing schemes in terms of robustness.

Heterogeneous networks of connected and autonomous vehicles.
In Section 4.2, we have presented a bio-inspired routing algorithm to enhance the lifetime of inter-UAVs communication links to deliver timely information to the ground base stations. However, due to the varying densities of UAVs in the target coverage zone and their independent missions, and thus independent routes, the existence of a route that connects a UAV to its ground base station is not always guaranteed. Thus, we aim to integrate UAVs with Connected and Autonomous Vehicles on the ground (CAVs) to build a heterogeneous network to further enhance the routing quality by providing alternative routes to broken air connection among UAVs. Typical use cases of this heterogeneous network are highways traffic monitoring, borders monitoring and most recently, citizens' mobility monitoring during COVID-19 pandemic to ensure that lockdown rules are respected. In particular, solutions will be developed to enable CAVs usage to extend the connectivity and coverage of UAVs to accomplish their mission successfully. We will investigate new ways of developing routing techniques that ensure both the quality and stability, despite the mobility and external factors that affect the connectivity of UAVs, of the UAV' selected route to deliver timely information to distant ground base stations with the required QoS. To this end, we will consider two heterogenous network scenarios: routing with known and partially known mobility models.

Machine learning for routing decision-making in UAV networks.
Current and future uses for UAVs include the collection of data from remote sensor networks deployed in agriculture fields for example, automated traffic monitoring and last-mile delivery. These uses may be performed by a network of collaborative UAVs and require UAVs with increased autonomy to plan and dynamically adapt their missions

and flight paths to best use their limited flight time in response to some factors such as collected data, changes in weather conditions and hardware failure. To fulfil these autonomous abilities in decision-making regarding path planning, we aim to take a promising approach by integrating machine learning in UAV' route selection process. The objective is to predict the moves of other UAVs through factors similar to the previously mentioned ones, and then estimate some more stable routing paths in terms of ground base stations accessibility and with better transmission capacity to cope with real-time transmission requirements of some UAV application domains.

Appendix A

Summary of some other works

This manuscript mainly focuses on my research contributions within my own supervised PhD thesis. However, I have been involved in a number of other works mainly within international collaborations and other co-supervised PhD thesis. They are closely related to my main research activity and some of them are briefly described in the following.

Safety enhancement in vehicular networks [5][6].
One of the major challenges in Vehicular Ad hoc Networks (VANETs) is to find a stable and robust Cooperative Collision Avoidance (CCA) scheme to address the rising death toll caused by road accidents every year. With *Shahab Haider*, *Ghulam Abbas* and *Ziaul Haq Abbas* from *GIKI Institute*, and *Thar Baker* from *Liverpool John Moores University*, we carried out works on improving road safety with effective mechanisms to detect and predict dangerous situations. To this end, we have proposed a Probabilistic Direction-Aware Cooperative Collision Avoidance (P-DACCA) scheme that takes into account realistic bi-directional traffic. The scheme starts with formation of dynamic clusters by incorporating Hamming distance in the k-medoids algorithm as an additional metric for direction awareness. After clustering, relative distances and speeds of nodes with respect to their expected states are computed. The scheme then estimates a collision probability on the basis of a node's expected state and provides an early warning message when the probability exceeds a predefined threshold. Moreover, we have proposed a Priority-based Direction-aware Media Access Control (PDMAC) as a novel protocol for intra-cluster and inter-cluster clock synchronization. It is a three-tier priority assignment technique to enhance warning messages delivery by taking into account the direction component, message type, and severity level on each tier.

Security in vehicular networks [4][23].

Ensuring safety in vehicular ad hoc networks (VANETs) requires the connected vehicles to exchange real time accurate road information. However, this necessity risks the privacy and may violate the user's confidentiality. The periodically broadcasted beacon messages containing the vehicle's spatiotemporal road information, and signed using the vehicle's temporal public key are the main factors leading to that risk. Since these factors are fundamental for the correct functioning of a vehicular network and, hence, cant' be ignored, solutions that preserve the location privacy are needed. With *Leila Benarous* and *Banamar Kadri* from the university of *Tlemcen*, we aimed to preserve the location privacy through a robust pseudonym change strategy that ensures the unlinkability. The proposed method confuses the attacker at the pseudonym update phase to thwart the linkability by combining the "hiding within the crowd" and the "location obfuscation" techniques.

Multi-Channel assignment in WBANs [9].

Traditional single channel communication in WSNs offers limited network throughput due to frequent interferences and congestion caused by concurrent transmissions in the same neighborhood. On the one hand, successful packet delivery requires mostly multiple retransmissions because of frequent collisions which also uses much battery. On the other hand, concurrent transmissions over multiple channels not only offer better network throughput and delays, but also reduce power consumption as packet collisions are minimized or eliminated depending upon the efficiency of the concerned channel assignment scheme. This may ensure QoS requirements of transmissions demanding high bandwidth and those that are delay sensitive such as in the case of Wireless Body Area Networks. To this end and with my former PhD student *Audace Manirabona* from the university of *Burundi*, we have considered a multiple channel WBAN network and proposed *GATE*, a theoretical game approach to adapt the channel bandwidth to the volume traffic requirement. In this way, medical video and audio traffics which are likely to be much bandwidth consumer are mainly considered using their priority classes.

Interference management in WBANs [31].
Interferences have significant impact on the reliability of packet transmissions in wireless communications. Due to very low power communication, wireless body area networks are potentially susceptible to interfere with coexisting wireless systems, including other WBANs that might exist in their vicinity. With *Kahina Haddadi* and *Hassine Moungla* from the university *Paris Descartes*, we have used cognitive radios (CRs) for proactive interference sensing in such systems. Our approach ensures the channel quality evaluation reducing the packet loss rate and mitigating interferences. On one hand, the intra-WBAN interference is managed through FTDMA protocol. On the other hand, if a high intensity of interference is detected, the proposed solution allows switching to another transmission channel, thereby ensuring the coexistence of WBANs.

Stereo image coding in wireless sensor networks [8][59].
One of the potential 3D imaging techniques relies on the use of stereoscopic systems. The great interest in these systems has resulted in huge amounts of data which need to be compressed for storage and transmission purposes. As part of *Ismaïl Bezzine*'s thesis and in collaboration with my colleagues *Mounir Kaaniche* and *Azeddine Beghdadi*, we worked on the improvement of the bitrate for real-time stereo image transmission by considering the coding of stereoscopic images in the context of urban video surveillance platforms based on wireless multimedia sensors. To this end, vector lifting scheme has been found to be an efficient approach for stereo image coding. For instance, the coding performance depends on the design of the involved lifting operators referred to as prediction and update filters. For this reason, while a non separable vector lifting structure is retained, we investigate different techniques for optimizing sparse criteria to design the filters used with both views. More precisely, an independent full optimization algorithm as well as a joint algorithm were developed and studied. Simulations performed on different stereo images demonstrate the effectiveness of the proposed sparse optimization techniques in terms of quality of reconstruction and bitrate saving.

Capacitated Network Design Problem [12][14][29][33].
With *Meriem Khelifi* from the university of *Annaba* and in collaboration with my colleague *Mohand Yazid Saidi*, we dealt with modular Capacitated Network Design Problem (modular CNDP). The objective was to determine a network topology allowing

the routing of a set of commodities (requests) between several sources and destinations while minimizing a metric combining three criteria: the cost of links to be established, the cost of the modules to be installed on each link and the routing of commodities. In fact, on each established link, a set of modules with different capacities and costs are chosen to ensure the routing of all commodity flows. In order to solve this NP-hard problem, we adopted approaches based on meta-heuristics and linear programming. By subdividing the CNDP problem into two sub-problems which consist in a first step in designing a set of network topologies which are validated and evaluated in a second step by the calculation of the best routing ensuring the satisfaction of all the commodities, we have developed a hybrid heuristic combining genetic algorithms with linear programming. We applied the genetic algorithms to generate a multitude of network topologies (sets of links and associated modules) that we subsequently evaluated by solving the multi-commodity flow problem in polynomial time with the use of linear programming.

Appendix B

Publications

In addition to the list of my publications below, three journal papers are under review and number of other works are submitted to international conferences to be held in 2021. These submitted works are mainly related to recently finished thesis (*Ismaïl Bezzine*) and to other thesis which are still ongoing (*Nouman Bashir* and *Fatima Zahra Rabahi*).

- **Book chapters**

  1. Saadi Boudjit, Hassine Moungla. (2015): "mHealth : WBANs' Issues and Challenges", Chapter in the book "Mobile Health : A Technology Road Map", Springer Series in Bio-Neuroinformatics, Vol. 5, pp. 771-790, Springer, February 2015.
  2. Salim Allal, Saadi Boudjit. (2013): "GeoSUZ: A Geocast Routing Protocol in Sub-ZORs for VANETs", In advanced Infocomm Technology, Volume 7593 of Lecture Notes in Computer Science, pp. 319-329, Springer, 2013.

- **Articles in international journals**

  3. Fatima Zahra Rabahi, Saadi Boudjit, Chemseddine Bemmoussat, Mohamed Benaissa (2020): "A 3-D Mobility Model in Flying Ad-hoc Networks for Real-time Emergency Applications", To be published in International Journal of Telecommunications and Radio Engineering, BegellHouse, December 2020.
  4. Leila Benarous, Benamar Kadri, Saadi Boudjit (2020): "Camouflage-based location privacy preserving scheme in Vehicular Ad hoc Networks", To be

published in International Journal of Vehicle Information and Communication Systems (IJVICS), Inderscience, December 2020.

5. Ghulam Abbas, Ziaul Haq Abbas, Shahab Haider, Thar Baker, Saadi Boudjit, Fazal Muhammad (2019): "PDMAC: A Priority-Based Enhanced TDMA Protocol for Warning Message Dissemination in VANETs", Sensors International Journal, Vol. 20, N.1, pp. 45, MDPI, December 2019.
6. Shahab Haider, Ghulam Abbas, Ziaul Haq Abbas, Saadi Boudjit, Zahid Halim (2019): "P-DACCA: A Probabilistic Direction-Aware Cooperative Collision Avoidance Scheme for VANETs", International Journal of Future Generation Computer Systems (FGCS), Vol. 103, pp. 1-17, ScienceDirect, December 2019.
7. Audace Manirabona, Saadi Boudjit, Lamia Chaari (2018) : "NetBAN, a concept of network of BANs for cooperative communication: energy awareness routing solution", International Journal of Ad Hoc and Ubiquitous Computing (IJAHUC), Vol. 8, No. 2, pp. 120-130, Inderscience, 2018.
8. Ismaïl Bezzine, M. Kaaniche, S. Boudjit, A. Beghdadi (2018) : "Sparse optimisation of non separable vector lifting scheme for stereo image coding", International Journal of Visual Communication and Image Representation, Vol. 57, pp. 283-293, ScienceDirect, 2018.
9. Audace Manirabona, Saadi Boudjit (2018) : "GATE, a game theory approach on traffic volume aware channel width adaptation for WBAN medical applications", International Journal of Communication Systems, Vol. 31, No. 11, Wiley, 2018.
10. Nour E. Bahloul, Saadi Boudjit, Marwen Abdennebi, Djallel Eddine Boubiche (2018) : "A Flocking-based on Demand Routing Protocol for Unmanned Aerial Vehicles", International Journal of Computer Science and Technology, Vol. 23, No. 2, pp. 263-276, Springer, 2018.
11. Lamia Chaari, Audace Manirabona, Saadi Boudjit (2017) : "Investigations on Healthcare Monitoring Systems: Innovative Services and Applications", International Journal of E-Health and Medical Communications (IJEHMC), Vol 8, No1, pp. 1-18, IGI Global, 2017.
12. Meriem KHELIFI, Mohand Yazid Saidi, Saadi Boudjit (2017) : "Solving the Capacitated Network Design Problem in Two Steps", International Journal

of Advances in Science, Technology and Engineering Systems (ASTESJ), Vol. 2, Issue 3, pp. 291-301, WordPress, 2017.

13. Saadi Boudjit, Anis Harfouche, Azeddine Beghdadi (2017): "A Lightweight Routing Protocol for a Multi-hop Wireless Video Surveillance Platform: Implementation, Experiments and Perspectives", EAI Endorsed Transactions on Ambient Systems, Vol. 4, No. 13, pp. e4, EAI, 2017.
14. M. Khelifi, M. Babes, S. Ghanemi, M.Y. Saidi, S. Boudjit (2015) : "Hybrid heuristic for Capacitated Network Design Problem", International Journal of High Speed Networks, Volume 21, No 4, pp. 313-330, IOS Press, 2015.
15. Yasir Faheem, Saadi Boudjit (2015): "Duty-Cycle SN-multi-point relay algorithm for mobile sink wireless sensor networks", International Journal of Wireless Sensor Systems, Volume 5, Issue 5, pp. 219-227, Print ISSN 2043-6386, IET, 2015.
16. Hadda Ibn Elhadj, Lamia Chaari, Saadi Boudjit, Lotfi Kamoun. (2015) : "Node and Hub Data Gathering Architectures for Healthcare Applications based on IEEE 802.15.6 Standard", International Journal of E-Health and Medical Communications (IJEHMC), Volume 6, Issue 3, pp. 38-62, IGI Global, 2015.
17. Salim Allal, Saadi Boudjit (2013) : " Geocast Routing Protocols for VANETs: Survey and Geometry-Driven Scheme Proposal", Internationl Journal of Internet Services and Information Security (JISIS), Vol.3, No.12-02, pp. 20-36, ISYOU/ISEP-IPP, 2013.
18. Saadi Boudjit (2013): "Autoconfiguration Protocol for a Multiple Interfaces Ad hoc Network Running OLSR Routing Protocol", International Journal of Computer Networks & Communications (IJCNC) Vol.5, No.1, pp. 153-170, AIRCC, 2013.
19. Saadi Boudjit, Cedric Adjih, Paul Muhlethaler, Anis Laouiti (2007): "Duplicate address detection and autoconfiguration in OLSR", International Journal of Universal Computer Science (JUCS), Vol.13, No.1, pp. 4-31, 2007.

- **Articles in international conferences**

20. Nouman Bashir, Saadi Boudjit, Mohand Yazid Saidi: "A Distributed Anticipatory Life-Enhancing Recovery Approach for Unmanned Aerial Vehicular

Networks", Proceedings of 18th IEEE CCNC 2021 conference, Las Vegas, NV, USA, January 09-12, 2021.

21. Fatima Zahra Rabahi, Saadi Boudjit, Chemseddine Bemmoussat, Mohamed Benaissa: "UAVs-Based Mobile Radars for Real-Time Highways Surveillance", Proceedings of the 17th IEEE MASS 2020 conference, Delhi NCR, India, December 10-13, 2020.
22. Nouman Bashir, Saadi Boudjit: "A Collision Avoiding Packet Scheduling and Energy-Efficient Routing Technique for Video Wireless Sensor Networks", 2020 International Symposium on Networks, Computers and Communications (ISNCC), pp. 1-6, Montreal, QC, Canada, October 20-22, 2020.
23. Leila Benarous, Benamar Kadri, Saadi Boudjit : "Alloyed Pseudonym Change Strategy for Location Privacy in VANETs", Proceedings of 17th IEEE CCNC 2020 conference, pp. 1-6, Las Vegas, NV, USA, January 10-13, 2020.
24. Nouman Bashir, Saadi Boudjit : "An Energy-Efficient Collaborative Scheme for UAVs and VANETs for Dissemination of Real-Time Surveillance Data on Highways", Proceedings of 17th IEEE CCNC 2020 conference, pp. 1-6, Las Vegas, NV, USA, January 10-13, 2020.
25. Nour E. Bahloul, Nouman Bashir, Saadi Boudjit, Djallel-Eddine Boubiche : "A Simple Proactive Routing Protocol with Multiple Base Stations Deployment for Unmanned Aerial Vehicular Networks", Proceedings of 11th IEEE Global Information Infrastructure Symposium, GIIS 2019, pp. 1-6, Paris, France, December 18-20, 2019.
26. Saadi Boudjit, Marwen Abdennebi, Ken Chen : "Performance Evaluation through Simulation of SN-MPR Routing Protocol for Restricted Areas", Proceedings of 6th IEEE International Conference on Information and Communication Technologies for Disaster Management, ICT-DM 2019, pp. 1-7, Paris, France, December 18-20, 2019.
27. Amira Bendjeddou, Houria Laoufi, Saadi Boudjit : "LEACH-S : Low Energy Adaptive Clustering Hierarchy for Sensor Networks", Proceedings of IEEE International Symposium on Networks, Computers and Communications (ISNCC 2019), pp. 1-6, Rome, Italy, June 19-21, 2018.
28. Nour El Houda Bahloul, Saadi Boudjit, Marwen Abdennebi and Djallel Eddine Boubiche : "Bio-inspired on demand routing protocol for Unmanned

Aerial Vehicles", Proceedings of 26th IEEE ICCCN 2017 conference, pp. 1-6, Vancouver, Canada, July 31-August 3, 2017.

29. Meriem Khelifi, Mohand Yazid Saidi, Saadi Boudjit: "Genetic algorithm based model for capacitated network design problem", 24th International Conference on Software, Telecommunications and Computer Networks, SoftCOM 2016, pp. 1-6, Split, Croatia, September 22-24, 2016.
30. Anis Harfouche, Saadi Boudjit, Azeddine Beghdadi : "Data Dissemination in a Wireless Video Surveillance Platform for Elderly Monitoring: Implementation and Experiments", 2nd EAI International Conference on Smart Objects and Technologies for Social Good, (GoodTechs) 2016, pp. 176-185, Venice, Italy, November 30 - December 1, 2016.
31. Hassine Moungla, Kahina Haddadi, Saadi Boudjit : "Distributed Interference Management in Medical Wireless Sensor Networks", In Proceedings of 13th IEEE CCNC 2016 conference, pp. 158-162, Las Vegas, Nevada, USA, January 2016.
32. Audace Manirabona, Saadi Boudjit, Lamia Chaari : "A Priority-Weighted Round Robin scheduling strategy for a WBAN based Healthcare Monitoring System", Proceedings of 13th IEEE CCNC 2016 conference, pp. 231-236, Las Vegas, Nevada, USA, January 2016.
33. M. Khelifi, S. Boudjit, M. Y. Saidi : "Two level Evolutionary Algorithm for Capacitated Network Design Problem", Proceedings of 13th IEEE CCNC 2016 conference, pp. 306-307, Las Vegas, Nevada, USA, January 2016.
34. H. Ibn Elhadj, N. Bradai, S. Boudjit, L. Chaari, L. Kamoun: "A Priority Based Cross Layer Data Dissemination Protocol for Healthcare Applications", Proceedings of 12th IEEE CCNC 2015, pp. 615-616, Las Vegas, Nevada, USA, January 2015.
35. N. Bradai, H. Ibn Elhadj, S. Boudjit, L. Chaari, L. Kamoun: "QoS Architecture over WBANs for Remote Vital Signs Monitoring Applications", Proceedings of 12t IEEE CCNC 2015, pp. 1-6, Las Vegas, Nevada, USA, January 2015.
36. Audace Manirabona, Saadi Boudjit, Lamia Chaari : "Energy aware routing protocol for inter WBANs cooperative communication", Proceedings of IEEE

International Symposium on Networks, Computers and Communications (ISNCC 2015), pp. 1-6, Hammamet, Tunisia, May 13-15, 2015.

37. Audace Manirabona, Lamia Chaari, Saadi Boudjit : "Decode and Merge Cooperative MAC Protocol for intra WBAN Communication", Proceedings of 16th IEEE International Conference on e-Health Networking, Applications and Services (IEEE Healthcom), pp. 146-151, Natal, Brasil, October 2014.
38. Hadda Ibn Elhadj, Saadi Boudjit, Lamia Chaari, Lotfi Kamoun : "IEEE 802.15.6 based Node and Hub Architectures for Healthcare Applications", Proceedings of 7th IEEE International Wireless Days conference, pp. 1-3, Rio De Janeiro, Brasil, November 2014.
39. Hadda Ibn ElHadj, Saadi Boudjit, Lamia Chaari : "A Cross-Layer Based Data Dissemination Algorithm For IEEE 802.15.6 WBANs", Proceedings of 4th IEEE international conference on Smart Communications in Network Technologies, SaCoNeT 2013, pp. 1-6, Paris, France, June 2013.
40. Nourchène Bradai, Lamia Chaari, Saadi Boudjit, Lotfi Kamoun : "New priority Mac protocol for wireless body area networks", Proceedings of 3rd International ACM MobiHoc workshop on Pervasive wireless healthcare, MobileHealth 2013, pp. 1-6, Bangalore, India, August 2013.
41. Salim Allal, Saadi Boudjit : "GeoSUZ: A Geocast Routing Protocol in SubZORs for VANETs", Proceedings of 5th IEEE International Conference on Advanced Infocomm Technology (ICAIT 2012), Revised Papers, pp. 319-329, Paris, France, July 2012.
42. Salim Allal, Saadi Boudjit : "Geocast Routing Protocols for VANETs: Survey and Guidelines", Proceedings of 6th International Conference on Innovative Mobile and Internet Services in Ubiquitous Computing (IMIS 2012), pp. 323-328, Palermo, Italy, July 2012.
43. Saadi Boudjit, Nadjim Chelghoum, Miloud Otsmani, Salim Allal : "Multi-Sensors' Data Gathering Management System for a Wireless Health Monitoring Platform", Proceedings of 1st International ACM MobiHoc workshop on Pervasive wireless healthcare, MobileHealth 2011, pp. 4, Paris, France, May 2011.
44. Yasir Faheem, Saadi Boudjit : "TABA: A Channel Selection Algorithm for

Heterogeneous Wireless Sensor Networks", Proceedings of ACM MobiHoc 2011 conference, Paris, France, May 2011.

45. Yasir Faheem, Saadi Boudjit : "Traffic-aware Adaptive-Bandwidth Channel Selection Algorithm for Wireless Sensor Networks", Proceedings of IWSOS 2011 conference, Karlsruhe, Germany, March 2011.
46. Yasir Faheem, Saadi Boudjit, Ken Chen : "Dynamic Sink Location Update Scope Control Mechanism for Mobile Sink Wireless Sensor Networks", Proceedings of IEEE WONS 2011 conference, Bardonnecchia, Italy, January 2011.
47. Yasir Faheem, Saadi Boudjit : "SN-MPR: A Multi-Point Relay Based Routin Protocol for Sensor Networks", Proceedings of IEEE CPScom 2010 conference, Hangzhou, China, December 2010.
48. Yasir Faheem, Saadi Booudjit : "Wireless Body Area Networks: Information Dissemination Analysis" Proceedings of IEEE HealthINF 2010 conference, Janvier 2010, Valencia, Spain, January 2010.
49. Yasir Faheem, Saadi Boudjit, Ken Chen : "Data Dissemination Strategies in Mobile Sink Wireless Sensor Networks: A Survey" - Proceedings of IEEE/IFIP Wireless Days 2009 conference, Paris, France, December 2009.
50. Saadi Boudjit, Cedric Adjih, Paul Muhlethaler : "DAD-MPR flooding protocol, Convergence Evaluation through Simulation", Proceedings of AINTEC'2007 conference, Phuket, Thailand, November 2007.
51. Georgios Rodolakis, Cedric Adjih, Saadi Boudjit, Anis Laouiti : "Quality-of-Service Multicast Overlay Spanning Tree Algorithms for Wireless Ad Hoc Networks", Proceedings of AINTEC'2007 conference, Phuket, Thailand, November 2007.
52. Saadi Boudjit, Cedric Adjih, Paul Muhlethaler, Anis Laouiti : "Autoconfiguration protocol for a multiple interfaces OLSR Network", Proceedings of 13th European Wireless Conference (EW-2007), Paris, France, April 2007.
53. Raghav Bhaskar, Daniel Augot, Cedric Adjih, Paul Muhlethaler, Saadi Boudjit : "AGDH (Asymmetric Group Diffie Hellman) An Efficient and Dynamic Group Key Agreement Protocol for Ad hoc Networks", Proceedings of First International Conference on New Technologies, Mobility and Security

(NTMS'2007), Paris, France, May 2007.

54. Saadi Boudjit, Anis Laouiti, Paul Muhlethaler, Cedric Adjih: "Duplicate address detection and autoconfiguration in OLSR", Proceedings of IEEE SNPD/SAWN 2005 conference, : pp. 403-410, Maryland, USA, May 2005.
55. S. Boudjit, A. Laouiti, P. Muhlethaler, C. Adjih : "An Implementation of a Simple Duplicate Address Detection and Autoconfiguration Mechanism for OLSR", 2nd OLSR Interop Workshop, In conjunction with the 63rd IETF meeting, Paris, France, July 2005.
56. Saadi Boudjit, Anis Laouiti, Paul Muhlethaler, Cedric Adjih : "Duplicate address detection with multiple conflicts and autoconfiguration in OLSR", Proceedings of IEEE/ICSIT'05 conference, pp. 24-30, Algiers, Algeria, July 2005.
57. Saadi Boudjit, Cedric Adjih, Anis Laouiti, Paul Muhlethaler : "A duplicate address detection and autoconfiguration mechanism for a single-interface OLSR network", Proceedings of AINTEC'2005 conference, pp. 128-142, Bangkok, Thailand, December 2005.
58. Anis Laouiti, Saadi Boudjit, Pascale Minet, Cedric Adjih : "OLSR for IPv6 networks", Proceeding of MedHoc-Net'2004 workshop, pp. 460-469, Bodrum, Turkey, June 2004.

- **Articles in national conferences**

59. Ismaïl Bezzine, Mounir Kaaniche, Noor Al-Maadeed, Saadi Boudjit, Azeddine Beghdadi : "Joint optimization of lifting operators for stereo image coding", CORESA 2018 (COmpression et Représentation des Signaux Audiovisuels), Poitiers, France, November 12-14, 2018.

- **IETF Standardization**

60. Saadi Boudjit, J-L. Rougier, H. Ali, A. Busson : "Internet-Draft: Link Monitoring in OLSR Protocol for Highly Dynamic Environments", Contribution to the MANET working group at IETF, June 2007.
61. Cedric Adjih, Saadi Boudjit, Philippe Jacquet, Anis Laouiti, Paul Muhlethaler : "Internet-Draft: Address autoconfiguration in Optimized Link

State Routing Protocol", Contribution to the MANET working group at IETF, February 2005.

62. Cedric Adjih, Saadi Boudjit, Pr. Mase, Philippe Jacquet, Anis Laouiti, Paul Muhlethaler :"Internet-Draft: Address autoconfiguration in Optimized Link State Routing Protocol", Contribution to the MANET working group at IETF, July 2005.

- **INRIA Research Reports**

63. Raghav Bhaskar, Paul Muhlethaler, Daniel Augot, Cedric Adjih, Saadi Boudjit : "Efficient and Dynamic Group Key Agreement in Ad hoc Networks", INRIA Research Report, RR-5915, May 2006.
64. Cedric Adjih, Saadi Boudjit, Philippe Jacquet, Anis Laouiti, Paul Muhlethaler : "An Advanced Configuration and Duplicate Address Detection mechanism for a multi-interfaces OLSR Network", INRIA Research Report, RR-5747, November 2005.
65. Saadi Boudjit, Anis Laouiti, Paul Mühlethaler, Cédric Adjih : "Duplicate address detection and autoconfiguration in OLSR", INRIA Research Report, RR-5475, January 2005.
66. Saadi Boudjit : Etude et simulation d'un schéma de réservation de bande passante dans les réseaux adhoc", INRIA Research Report, RR-4102, January 2001.

- **Other Research Reports**

67. Yasir Faheem, Saadi Boudjit, Ken Chen: "Wireless multimedia sensor networks : requirements and current paradigm", THD Research Report, March 2010, (http://www.portailthd.fr/media/uploads/2010/06/24/fichereseaux-de-capteurs.pdf).

References

[1] Ieee std 802.15.4-2006. wireless medium access control (mac) and physical layer (phy) specifications for low-rate wireless personal area networks (wpans), 2006.

[2] Ieee 802.15.6 wpan task group 6 (tg6) - body area networks. ieee standard for local and metropolitan area networks - part 15.6: Wireless body area networks. www.ieee802.org/15/pub/tg6.html, 2012.

[3] Aftab Ali and Farrukh Aslam Khan. Energy-efficient cluster-based security mechanism for intra-wban and inter-wban communications for healthcare applications. *EURASIP J. Wireless Comm. and Networking*, 2013:216, 2013.

[4] Abdel Ilah Alshbatat and Liang Dong. Cross layer design for mobile ad-hoc unmanned aerial vehicle communication networks. In *Proceedings of the IEEE International Conference on Networking, Sensing and Control, ICNSC 2010, Chicago, IL, USA, 10-12 April 2010*, pages 331– 336. IEEE, 2010.

[5] G. Anastasi, A. Falchi, A. Passarella, M. Conti, and E. Gregori. Performance measurements of motes sensor networks. In *Proceedings of the 7th ACM international symposium on Modeling, analysis and simulation of wireless and mobile systems*, MSWiM '04, pages 174–181, New York, NY, USA, 2004. ACM.

[6] Liliana M. Arboleda C. and Nidal Nasser. Cluster-based routing protocol for mobile sensor networks. In *Proceedings of the 3rd international conference on Quality of service in heterogeneous wired/wireless networks*, QShine '06, New York, NY, USA, 2006. ACM.

[7] T. Atechian. Dg-castor: Direction-based geocast routing protocol for query dissemination in vanet. 4th International Workshop on Localized Communication and Topology Protocols for Ad hoc Networks, 2008.

[8] Karp B. and Kung H. T. Gpsr: greedy perimeter stateless routing for wireless networks. Proceedings of the 6th annual international conference on Mobile computing and networking pages, 243-254, 2000.

[9] Karthikeyan B, Kanimozhi N, and Ganesh S H. Analysis of reactive aodv routing protocol for manet. In *IEEE World Congress on Computing and Communication Technologies, Trichirappalli, India, 27 Feb.-1 March 2014*, pages 264 – 267, 2014.

[10] A. Bachir and A. Benslimane. A multicast protocol in ad hoc networks inter-vehicle geocast. Vehicular Technology Conference, 2003. VTC 2003-Spring. The 57th IEEE Semiannual, vol. 4, pp. 2456-2460, 2003.

[11] H. Ben Elhadj, S. Boudjit, and L. C. Fourati. A cross-layer based data dissemination algorithm for ieee 802.15.6 wbans. In *2013 International Conference on Smart Communications in Network Technologies (SaCoNeT), June 17-19, Paris, France*, volume 01, pages 1–6, 2013.

[12] Roberto Beraldi, Roberto Baldoni, and Ravi Prakash. A biased random walk routing protocol for wireless sensor networks: The lukewarm potato protocol. *IEEE Trans. Mob. Comput.*, 9(11):1649–1661, 2010.

[13] Anthony Busson, Nathalie Mitton, and Eric Fleury. Analysis of the multi-point relay selection in olsr and implications. In *Challenges in Ad Hoc Networking - Fourth Annual Mediterranean Ad Hoc Networking Workshop, June 21-24, 2005, Île de Porquerolles, France*, pages 387–396. Springer, 2005.

[14] Mengyuan C., Jun H. D. F., Yao Z., and Xiaoyang Z. An ultra low-power and area-efficient baseband processor for wban transmitter. In *Signal and Information Processing Association Annual Summit and Conference (APSIPA)*, pages 1–4, Asia-Pacific, November 2013.

[15] T. Leinmuller C. Maihofer and E. Schoch. Abiding geocast: time–stable geocast for ad hoc networks. Proceedings of the 2nd ACM international workshop on Vehicular ad hoc networks, pp. 20–29, 2005.

[16] Y. M. Chen and Y. J. Peng. Energy efficient fuzzy routing protocol in wireless body area networks. *International Journal of Engineering and Applied Sciences*, 4(1), 07 2013.

[17] Y. S. Chen, Y. W. Lin, and S. L. Lee. A mobicast routing protocol for vehicular ad hoc networks. ACM/Springer Mobile Networks and Applications (MONET), vol. 15, no. 1, pp. 20–35, 2010.

[18] Jae-Myeong Choi, Heau-Jo Kang, and Yong-Seok Choi. A study on the wireless body area network applications and channel models. In *The Second International Conference on Future Generation Communication and Networking, FGCN 2008, Volume 2, Workshops, Hainan Island, China, December 13-15, 2008*, pages 263–266. IEEE Computer Society, 2008.

[19] Thomas Clausen and Philippe Jacquet. Optimized link state routing protocol (olsr). RFC 3626, Internet Engineering Task Force, October 2003.

[20] Smith D. and Miniutti D. Cooperative body-area-communications: First and second-order statistics with decode-and-forward. In *IEEE Wireless Communications and Networking Conference (WCNC'12)*, Paris, France, April 2012.

[21] Gu Daniel, Pei Guangyu, Ly Henry, Gerla Mario, and Hong Xiaoyan. Hierarchical routing for multi-layer ad-hoc wireless networks with uavs. In *IEEE Military Communications Conference MILCOM 2000, Los Angeles, CA, USA, 22-25 Oct. 2000*, pages 310 – 314, 2000.

[22] F. De Rango, M. Fotino, and S. Marano. Ee-olsr: Energy efficient olsr routing protocol for mobile ad-hoc networks. In *MILCOM 2008 - 2008 IEEE Military Communications Conference, San Diego, CA, USA, 16-19 Nov. 2008*, pages 1–7, 2008.

[23] J. Elias and A. Mehaoua. Energy-aware topology design for wireless body area networks. In *2012 IEEE International Conference on Communications (ICC)*, pages 3409–3410, 2012.

[24] Chen Y. et al. Cooperative communications in ultra-wideband wireless body area networks: Channel modeling and system diversity analysis. *IEEE Journal on Selected Areas in Communications*, 27:5–16, January 2009.

[25] I. Ali et al. N. M. Khan. Quasi centralized clustering approach for an energy-efficient and vulnerability-aware routing in wireless sensor networks. In *Proceeding of the 1st ACM international workshop on heterogeneous sensor and actor networks*, 2008.

[26] J. Hope Forsmann, Robert E. Hiromoto, and John Svoboda. A time-slotted on-demand routing protocol for mobile ad hoc unmanned vehicle systems. In *Unmanned Systems Technology IX, Defense and Security Symposium 2007, Orlondo, Florida, USA, May 2007*, volume 6561, pages 530 – 540. International Society for Optics and Photonics SPIE, 2007.

[27] Andrew Fort, Julien Ryckaert, Claude Desset, Philippe De Doncker, Piet Wambacq, and Leo Van Biesen. Ultra-wideband channel model for communication around the human body. *IEEE J. Sel. Areas Commun.*, 24(4):927–933, 2006.

[28] Carles G., Antoni B., and Josep P. Impact of lqi-based routing metrics on the performance of a one-to-one routing protocol for ieee 802.15.4 multihop networks. *EURASIP Journal on Wireless Communications and Networking 2010*, 2010.

[29] Sai Anand G. and Jong-Tae P. Energy-efficient mac protocols for wireless body area networks: A survey. In *International Congress on Ultra-Modern Telecommunications and Control Systems and Workshops (ICUMT)*, pages 739–744, Oct 2010.

[30] M. L. Sichitiu H. P. Joshi and M. Kihl. Distributed robust geocast multicast routing for inter-vehicle communication. Proceedings of WEIRD Workshop on WiMax, Wireless and Mobility, pp. 9-21, 2007.

[31] K. Naik H. Rahbar and A. Nayak. Dtsg: Dynamic time-stable geocast routing in vehicular ad hoc networks. IEEE Symposium on Computers and Communications, pp. 198–203, 2010.

[32] Zhu Han, A. Lee Swindlehurst, and K. J. Ray Liu. Smart deployment/movement of unmanned air vehicle to improve connectivity in MANET. In *IEEE Wireless Communications and Networking Conference, WCNC 2006, 3-6 April 2006, Las Vegas, Nevada, USA*, pages 252–257. IEEE, 2006.

[33] Jie Hao, Zheng Yao, Kui Huang, Baoxian Zhang, and Cheng Li. An energy-efficient routing protocol with controllable expected delay in duty-cycled wireless sensor networks. In *Proceedings of IEEE International Conference on Communications, ICC 2013, Budapest, Hungary, June 9-13, 2013*, pages 6215–6219. IEEE, 2013.

[34] Vladimir Hottmar and Bohumil Adamec. Analytical model of a weighted round robin service system. *J. Electrical and Computer Engineering*, 2012:374961:1–374961:6, 2012.

[35] Songhua Hu and Jianghong Han. Power control strategy for clustering wireless sensor networks based on multi-packet reception. *IET Wireless Sensor Systems*, 4(3):122–129, 2014.

[36] Ozlem Durmaz Incel, Lodewijk van Hoesel, Pierre Jansen, and Paul Havinga. Mc-lmac: A multi-channel mac protocol for wireless sensor networks. *Ad Hoc Netw.*, 9(1):73–94, January 2011.

[37] Dong J. and Smith D. Cooperative receive diversity for coded gfsk body-area communications. *Electronics Letters*, 47:1098–1100, September 2011.

[38] Dong J. and Smith D. Cooperative body-area-communications: Enhancing coexistence without coordination between networks. In *IEEE International Symposium on Personal and Indoor Mobile Radio Conference (PIMRC)*, page 6, Sydney, Australia, September 2012.

[39] Dong J. and Smith D. Opportunistic relaying in wireless body-area networks: Coexistence performance. In *IEEE International Conference on Communications (ICC)*, pages 5613–5618, Budapest, September 2013.

[40] B. G. Laxmi J. Kakarla, S. S. Sathya and al. A survey on routing protocols and its issues in vanet. International Journal, vol. 28, no. 4, pp. 38-44, 2011.

[41] B. G. Laxmi J. Kakarla1, S. S. Sathya1 and R. Babu B. A survey on routing protocols and its issues in vanet. International Journal of Computer Applications (0975 –8887) Volume 28– No.4, 2011.

[42] A. Nayak J. Yang, X. Li and I. Stojmenovic. Localized location update for data fusion to a mobile sink in wireless sensor networks. Note. 2008.

[43] Nadeem Javaid, Z. Abbas, M. S. Fareed, Zahoor Ali Khan, and Nabil Ali Alrajeh. M-ATTEMPT: A new energy-efficient routing protocol for wireless body area sensor networks. In *Proceedings of the 4th International Conference on Ambient Systems, Networks and Technologies (ANT 2013), the 3rd International Conference on Sustainable Energy Information Technology (SEIT-2013), Halifax, Nova Scotia, Canada, June 25-28, 2013*, pages 224–231. Elsevier, 2013.

[44] Khan J.Y. and Yuce Mehmet. *Wireless Body Area Network (WBAN) for Medical Applications. New Developments in Biomedical Engineering.* IntechOpen, 01 2010.

[45] Chandrashekar K., Dekhordi M. R., and Baras J. S. Providing full connectivity in large ad-hoc networks by dynamic placement of aerial platforms. In *IEEE Military communication conference*, pages 1429–1436. IEEE, 2004.

[46] H. Ghim J. Hong H. Yoon K. Kweon. Gradient-based energy-efficient routing from multiple sources to multiple mobile sinks in wireless sensor networks. In *4th International Symposium on Wireless Pervasive Computing (ISWPC)*, 2009.

[47] Pervez Khan, Asdaque Hussain, and Kyung Sup Kwak. Medical applications of wireless body area networks. *International Journal of Digital Content Technology and its Applications JDCTA*, 3(3):185–193, 2009.

[48] Joohwan Kim, Xiaojun Lin, and Ness B. Shroff. Optimal anycast technique for delay-sensitive energy-constrained asynchronous sensor networks. *IEEE/ACM Trans. Netw.*, 19(2):484–497, 2011.

[49] Youngmin Kim, Hyojeong Shin, and Hojung Cha. Y-mac: An energy-efficient multi-channel mac protocol for dense wireless sensor networks. In *Proceedings of the 7th international conference on Information processing in sensor networks*, IPSN '08, pages 53–63, Washington, DC, USA, 2008. IEEE Computer Society.

[50] Erik Kuiper and Simin Nadjm-Tehrani. Geographical routing in intermittently connected ad hoc networks. In *22nd International Conference on Advanced Information Networking and Applications, AINA 2008, Okinawa, Japan, March 25-28, 2008*, pages 1690–1695. IEEE Computer Society, 2008.

[51] R. Kumar and M. Dave. A comparative study of various routing protocols in vanet. International Journal of Computer Science Issues (IJCSI), Vol. 8,Issue-4, No.-4, 2011.

[52] Hughes L., Wang X., and Chen T. A review of protocol implementations and energy efficient cross-layer design for wireless body area networks. *Sensors 2012*, pages 14730–14773, 2012.

[53] Lin L., Sun Qibo, Li J., and Yang F. A novel geographic position mobility oriented routing strategy for uavs. *Journal of Computational Information Systems, pp.709 – 716, vol.8, 2012.*

[54] Pinedo Michael L. *Scheduling: Theory, Algorithms, and Systems.* Springer Publishing Company, Incorporated, 3rd edition, 2012.

[55] Shouwen Lai and Binoy Ravindran. On distributed time-dependent shortest paths over duty-cycled wireless sensor networks. In *INFOCOM 2010. 29th IEEE International Conference on Computer Communications, Joint Conference of the IEEE Computer and Communications Societies, 15-19 March 2010, San Diego, CA, USA*, pages 1685–1693. IEEE, 2010.

[56] Benoît Latré, Ingrid Moerman, Bart Dhoedt, and Piet Demeester. Networking in wireless body area networks. In *5th FTW PHD Symposium*, 2004.

[57] Ching-Ju Lin, Po-Lin Chou, and Cheng-Fu Chou. Hcdd: hierarchical cluster-based data dissemination in wireless sensor networks with mobile sink. In *Proceedings of the 2006 international conference on Wireless communications and mobile computing*, IWCMC '06, pages 1189–1194, New York, NY, USA, 2006. ACM.

[58] Haiyun Luo, Fan Ye, Jerry Cheng, Songwu Lu, and Lixia Zhang. Ttdd: two-tier data dissemination in large-scale wireless sensor networks. *Wireless Networks*, 11:161–175, January 2005.

[59] T. Ekeroth M. Kihl, M. Sichitiu and M. Rozenberg. Reliable geographical multicast routing in vehicular ad hoc networks. Lecture Notes in Computer Science 4517 LNCS[C], pp. 315-325, 2007.

[60] A. Shaqfa M. Lakas. Geocache: Sharing and exchanging road traffic information using peer-to-peer vehicular communication. Vehicular Technology Conference (VTC Spring), 2011 IEEE 73rd, pp. 1 - 7, 2011.

[61] C. Maihofer and R. Eberhardt. Geocast in vehicular environments: Caching and transmission range control for improved efficiency. Proceedings of IEEE Intelligent Vehicles Symposium (IV), pp. 951–956, 2004.

[62] Jesús Iván Maza, Fernando Caballero, Jesús Capitán, J. Ramiro Martinez de Dios, and Aníbal Ollero. Experimental results in multi-uav coordination for disaster management and civil security applications. *Journal of Intelligent and Robotic Systems*, 61(1-4):563–585, 2011.

[63] Le Michael, Park Joon-Sang, and Gerla Mario. Uav assisted disruption tolerant routing. In *IEEE Military Communications Conference MILCOM 2006, Washington, DC, USA, 23-25 Oct. 2006*, pages 1–5, 2006.

[64] H. Moungla, N. Touati, and A. Mehaoua. Efficient heterogeneous communication range management for dynamic wban topology routing. In *2013 First International Symposium on Future Information and Communication Technologies for Ubiquitous HealthCare (Ubi-HealthTech)*, pages 1–5.

[65] C. K. Ng N. K. Noordin, A. B. Awwad. Cluster based routing protocol with adaptive scheduling for mobility and energy awareness in wireless sensor network. In *Proceedings of Network Research Workshop*, 2010.

[66] Kolar Purushothama Naveen and Anurag Kumar. Relay selection for geographical forwarding in sleep-wake cycling wireless sensor networks. *IEEE Trans. Mob. Comput.*, 12(3):475–488, 2013.

[67] Ferrand P., Maman M., Goursaud C., Gorce J.-M., and Ouvry L. Performance evaluation of direct and cooperative transmissions in body area networks. *Annals of Telecommunications*, 66:213–228, 2011.

[68] Chun-Su Park, Kwang-Wook Lee, You-Sun Kim, and Sung-Jea Ko. A route maintaining algorithm using neighbor table for mobile sinks. *Wireless Networks*, 15:541–551, May 2009.

[69] C. Perkins, E. Belding-Royer, and S. Das. Ad hoc on-demand distance vector (aodv) routing. In *IETF RFC*, page RFC 3561. RFC Editor, 2003.

[70] Amir Qayyum, Laurent Viennot, and Anis Laouiti. Multipoint relaying for flooding broadcast messages in mobile wireless networks. In *35th Hawaii International Conference on System Sciences (HICSS-35 2002), 7-10 January 2002, Big Island, HI, USA*, pages 3866–3875. IEEE Computer Society, 01 2002.

[71] Mark Hempstead Qin Wang and Woodward Yang. A realistic power consumption model for wireless sensor network devices. In *In Proceedings of the Third Annual IEEE Communications Society Conference on Sensor, Mesh and Ad Hoc Communications and Networks(SECON)*, Reston, VA, 2006.

[72] Derrico R., Rosini R., and Maman M. A performance evaluation of cooperative schemes for on-body area networks based on measured timevariant channels. In *in IEEE International Conference on Communications (ICC)*, pages 1–5, June 2011.

[73] E. Reusens, W. Joseph, G. Vermeeren, D. Kurup, and L. Martens. Real human body measurements, model, and simulations of a 2.45 ghz wireless body area network communication channel. In *2008 5th International Summer School and Symposium on Medical Devices and Biosensors*, pages 149–152, 2008.

[74] Craig W. Reynolds. Flocks, herds, and schools: a distributed behavioral model. *Computer Graphics*, 21(4):25–34.

[75] M. Salajegheh, H. Soroush, and A. Kalis. Hymac: Hybrid tdma/fdma medium access control protocol for wireless sensor networks. In *Personal, Indoor and Mobile Radio Communications, 2007. PIMRC 2007. IEEE 18th International Symposium on*, pages 1 –5, sept. 2007.

[76] V. Sharma and S. Khambra. Performance comparison of dsr, olsr and tora routing protocols. *International Journal of Scientific Technology Research*, vol. 3, issue 8, pp. 1546–1557, 2014.

[77] Rostam Shirani, Marc St-Hilaire, Thomas Kunz, Yifeng Zhou, Jun Li, and Louise Lamont. The performance of greedy geographic forwarding in unmanned aeronautical ad-hoc networks. In *Proceedings of the Ninth Annual Communication Networks and Services Research Conference, CNSR 2011, Ottawa, Ontario, Canada, 2-5 May 2011*, pages 161–166. IEEE Computer Society, 2011.

[78] Zhi Sun, Pu Wang, Mehmet C. Vuran, Mznah Al-Rodhaan, Abdullah Al-Dhelaan, and Ian F. Akyildiz. Bordersense: Border patrol through advanced wireless sensor networks. *Ad Hoc Networks*, 9(3):468–477, 2011.

[79] Fantina Tedim, Gavriil Xanthopoulos, and Vittorio Leone. Chapter 5 - forest fires in europe: Facts and challenges. In John F. Shroder and Douglas Paton, editors, *Wildfire Hazards, Risks and Disasters*, pages 77 – 99. Elsevier, 2015.

[80] Tsung-Yu Tsai, Yao-Liang Chung, and Zsehong Tsai. Introduction to packet scheduling algorithms for communication networks. In Jun Peng, editor, *Communications and Networking*, chapter 13. IntechOpen, 2010.

[81] Gill R. Tsouri, Alvaro Prieto, and Nikhil Argade. On increasing network lifetime in body area networks using global routing with energy consumption balancing. *Sensors*, 12(10):13088–13108, 2012.

[82] L.F.W. Hoesel van and P.J.M. Havinga. A lightweight medium access protocol (lmac) for wireless sensor networks: Reducing preamble transmissions and transceiver state switches. In *1st International Workshop on Networked Sensing Systems, INSS 2004*, pages 205–208, Tokio, Japan, 2004. Society of Instrument and Control Engineers (SICE).

[83] A. Chandrakasan W. Heinzelman and H. Balakrishnan. Energy-efficient communication protocol for wireless microsensor networks. In *Proceedings of the 33rd Hawaii International Conference on System Sciences (HICSS '00)*, January 2000.

[84] H. Geert W. K. Wolterink and K. Georgios. Constrained geocast to support cooperative adaptive cruise control (cacc) merging. Vehicular Networking Conference (VNC), 2010 IEEE, pp. 41-48, 2010.

[85] Guojun Wang, Tian Wang, Weijia Jia, Minyi Guo, Hsiao-Hwa Chen, and M. Guizani. Local update-based routing protocol in wireless sensor networks with mobile sinks. In *Communications, 2007. ICC '07. IEEE International Conference on*, pages 3094–3099, june 2007.

[86] Guojun Wang, Tian Wang, Weijia Jia, Minyi Guo, and Jie Li. Adaptive location updates for mobile sinks in wireless sensor networks. *Journal of Supercomputing*, 47:127–145, February 2009.

[87] Y. Wang and F. Li. Vehicular ad hoc networks. Guide to Wireless Ad Hoc Networks, Computer Communications and Networks. Springer, London, pp. 503 - 525, 2009.

[88] Ying-Hong Wang, Kuo-Feng Huang, Ping-Fang Fu, and Jun-Xuan Wang. Mobile sink routing protocol with registering in cluster-based wireless sensor networks. In *Proceedings of the 5th international conference on Ubiquitous Intelligence and Computing*, UIC '08, pages 352–362, Berlin, Heidelberg, 2008. Springer-Verlag.

[89] Hung Le Xuan and Sungyoung Lee. A coordination-based data dissemination protocol for wireless sensor networks. In *Intelligent Sensors, Sensor Networks and Information Processing Conference, 2004. Proceedings of the 2004*, pages 13–18, dec. 2004.

[90] Helen Yu-Zhang and Peter G. Harrison. Performance of a priority-weighted round robin mechanism for differentiated service networks. In *Proceedings of the 16th International Conference on Computer Communications and Networks, IEEE ICCN 2007, Turtle Bay Resort, Honolulu, Hawaii, USA, August 13-16, 2007*, pages 1198–1203. IEEE, 2007.

[91] Li Z., Peng Y., Qiao D., and Wensheng Zhang. Joint aggregation and mac design to prolong sensor network lifetime. In *Proc. IEEE ICNP'13*, Gottingen, Gernmany, October 2013.

[92] Jingbin Zhang, Gang Zhou, Chengdu Huang, S.H. Son, and J.A. Stankovic. Tmmac: An energy efficient multi-channel mac protocol for ad hoc networks. In *Communications, 2007. ICC '07. IEEE International Conference on*, pages 3554–3561, june 2007.

[93] Jinhua Zhu and Xin Wang. Model and protocol for energy-efficient routing over mobile ad hoc networks. *IEEE Trans. Mob. Comput.*, 10(11):1546–1557, 2011.